

Fault section identification method for the UHV GIL-overhead hybrid line

eISSN 2051-3305

Received on 28th August 2018

Accepted on 19th September 2018

E-First on 8th January 2019

doi: 10.1049/joe.2018.8693

www.ietdl.org

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Abstract: GIL-overhead hybrid transmission line is an essential way for UHV waters crossing power transmission over long distance in china. The fault section identification of the UHV GIL-overhead hybrid line is a previous work for the protection selective tripping and quick repair after fault. The characteristics of the electrical parameters in different sections of the UHV GIL-overhead hybrid line are analysed first. Regarding the joint of the UHV GIL-overhead hybrid line as the reference point, a fault section identification function is established. According to the characteristics of the complex plane derived from the function, a fault section identification method is proposed for the UHV GIL-overhead hybrid line. The accuracy of the fault section identification method is tested by simulation and the factors affecting the accuracy of the algorithm are analysed.

1 Introduction

The gas-insulated line (GIL) is a transmission system for the transmission at high-voltage level, with SF₆ or SF₆-N₂ gas mixture as the insulating medium and the conductor kept in the centre of the metallic enclosure [1]. Particularly, due to its high reliability, insulation-aging resistance and little environmental impact, the GIL suitably serves as the connections between power plants and substations, and deals with complicated landscapes [2, 3]. The GIL was used for UHV waters crossing power transmission for the first time around the world in SuTong UHV GIL Pipe Gallery Project in China. The electrical parameters and the fault characteristics of GIL and overhead transmission lines are quite different, so the fault section should be quickly identified and cooperated with reclosure after faulted, which is of great practical significance for improving the probability of reclosure, preventing system from the secondary impact caused by the reclosing failure, reducing the fault checking duration and speeding up the restoration of power supply.

The fault section identification method for the UHV GIL-overhead hybrid line in engineering generally installs a differential protection device at both ends of the GIL and cooperating with the differential protection device of the overhead line via the signal transmission devices. Due to the installation of more protection and signal transmission devices, there is an increase in cost correspondingly. In order to reduce the cost, the fault section identification method based on the electrical quantities of the two ends of the hybrid line had been attracted broad attention in the industry. Considering that there are few engineering projects of GIL-overhead hybrid line, the study on the fault section identification methods for the hybrid line generally points at cable-overhead hybrid line. Tang *et al.* [4] calculated the traveling time of the traveling wave by means of wavelet analysis and further proposed a fault locating method for the cable-overhead hybrid line. Huang *et al.* [5] proposed a fault location method based on double-ended traveling wave of the hybrid line. Both of these fault

location methods have the advantages of fast speed and little influence of transition resistance, but there are some shortcomings such as the wave front is not easy to be captured and easily affected by the multi-fold refraction and reflection at the boundary. The authors [6, 7] proposed a two-terminal fault locating method based on the distribution parameter model of the hybrid line. Wu *et al.* [8] examined the distribution characteristics of the positive sequence voltage amplitude along the hybrid line and proposed a fault detection algorithm. These fault location methods based on failure analysis above is easy to implement, but weak in computational complexity and false root identification.

This paper, based on an analysis of the electrical characteristics in different sections of the UHV GIL-overhead hybrid line, studies the fault section identification method applicable to this hybrid line and further tests the accuracy of this method by simulation.

2 Fault section identification function of the hybrid line

Take the UHV GIL-overhead hybrid line in SuTong UHV GIL Pipe Gallery Project as an example. The diagram of this hybrid line is shown as Fig. 1, where l_{m1} , l_{ij} and l_{nj} are, respectively, the length of the overhead line 1, GIL and overhead line 2; $\dot{E}_m$ and $\dot{E}_n$ are, respectively, the potential at both sides of the source; $\dot{V}_m$, $\dot{V}_n$, $\dot{I}_m$ and $\dot{I}_n$ are the voltages and currents at point m and point n correspondingly; $\dot{V}_i$, $\dot{V}_j$, $\dot{I}_i$ and $\dot{I}_j$ are the voltages and currents at point i (joint of the overhead line 1 and the GIL) and point j (joint of the overhead line 2 and the GIL). The positive sequence voltages and currents are present in this system no matter what happens on the line, so the positive sequence components will be adopted in the following deduction.

Take the positive sequence voltages and currents at point m and point n as known conditions, the positive sequence voltages and currents at point i and point j are calculated via the transmission line equation.

$$\begin{cases} \dot{V}_{i1} = \dot{V}_{m1} \times \cosh \gamma_1 l_{m1} - \dot{I}_{m1} Z_{C1} \times \sinh \gamma_1 l_{m1} \\ \dot{I}_{i1} = \frac{\dot{V}_{m1}}{Z_{C1}} \times \sinh \gamma_1 l_{m1} + \dot{I}_{m1} \times \cosh \gamma_1 l_{m1} \end{cases} \quad (1)$$

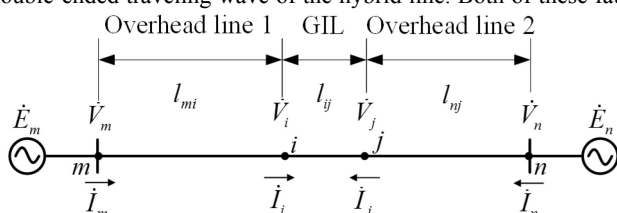


Fig. 1 Diagram of the UHV GIL-overhead hybrid line

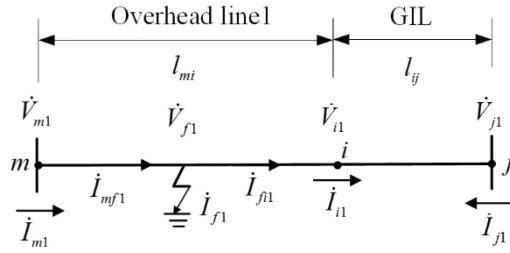


Fig. 2 Positive sequence model of hybrid segment 1

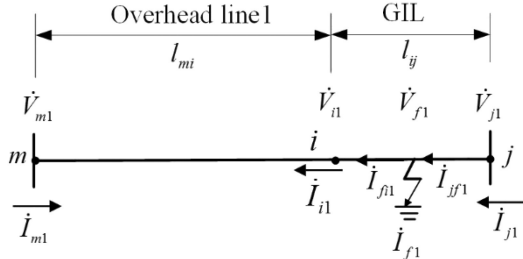


Fig. 3 Positive sequence model of hybrid segment 1 with fault located on GIL

$$\begin{cases} \dot{V}_{j1} = \dot{V}_{m1} \times \cosh \gamma_1 l_{mj} - \dot{I}_{m1} Z_{C1} \times \sinh \gamma_1 l_{mj} \\ \dot{I}_{j1} = -\frac{\dot{V}_{m1}}{Z_{C1}} \times \sinh \gamma_1 l_{mj} + \dot{I}_{m1} \times \cosh \gamma_1 l_{mj} \end{cases} \quad (2)$$

where $\dot{V}_{i1}$, $\dot{V}_{j1}$, $\dot{I}_{i1}$ and $\dot{I}_{j1}$ are the positive sequence voltages and currents at point i and point j correspondingly; Z_{C1} and γ_1 are, respectively, the positive sequence natural impedance and the positive sequence propagation constant of the overhead line. It can be expressed as

$$\begin{cases} Z_{C1} = R_1 + jX_1 \\ \gamma_1 = \alpha_1 + j\beta_1 \end{cases} \quad (3)$$

where R_1 , X_1 , α_1 and β_1 are the real and imaginary parts of the positive sequence natural impedance and the positive sequence propagation constant correspondingly.

A segment consists of overhead line 1 and GIL is referred to hybrid segment 1 and another consists of overhead line 2 and GIL is referred to hybrid segment 2. These two hybrid segments are analysed, respectively, to deduce the fault section identification function. The positive sequence model of hybrid segment 1 is illustrated in Fig. 2.

When a fault occurred on overhead line 1, the positive sequence voltage at the fault point f ($\dot{V}_{f1}$) and the positive sequence current to the left of point f ($\dot{I}_{mf1}$) are obtained via the positive sequence voltage and current at point m ($\dot{V}_{m1}$, $\dot{I}_{m1}$).

$$\begin{cases} \dot{V}_{f1} = \dot{V}_{m1} \times \cosh \gamma_1 l_{mf} - \dot{I}_{m1} Z_{C1} \times \sinh \gamma_1 l_{mf} \\ \dot{I}_{mf1} = -\frac{\dot{V}_{m1}}{Z_{C1}} \times \sinh \gamma_1 l_{mf} + \dot{I}_{m1} \times \cosh \gamma_1 l_{mf} \end{cases} \quad (4)$$

where l_{mf} is the distance from point m to point f.

According to the Kirchhoff's current law, the current equation of point f is

$$\dot{I}_{mf1} = \dot{I}_{f1} + \dot{I}_{fi1} \quad (5)$$

where $\dot{I}_{f1}$ is the positive sequence current at point f; $\dot{I}_{fi1}$ is the positive sequence current to the right of point f.

The positive sequence voltage and current at joint i ($\dot{V}_{i1}$, $\dot{I}_{i1}$) can be calculated via the voltage $\dot{V}_{f1}$ and the current $\dot{I}_{fi1}$.

$$\begin{cases} \dot{V}_{i1} = \dot{V}_{f1} \times \cosh \gamma_1 l_{fi} - \dot{I}_{fi1} Z_{C1} \times \sinh \gamma_1 l_{fi} \\ \dot{I}_{i1} = -\frac{\dot{V}_{f1}}{Z_{C1}} \times \sinh \gamma_1 l_{fi} + \dot{I}_{fi1} \times \cosh \gamma_1 l_{fi} \end{cases} \quad (6)$$

where l_{fi} is the distance from point f to point i.

By substituting (4) and (5) into (6), the relationship between the positive sequence voltage and current at joint i ($\dot{V}_{i1}$, $\dot{I}_{i1}$) and the positive sequence voltage and the current at point m ($\dot{V}_{m1}$, $\dot{I}_{m1}$) are obtained as (7)

$$\begin{cases} \dot{V}_{i1} = \dot{V}_{m1} \times \cosh \gamma_1 l_{mi} - \dot{I}_{m1} Z_{C1} \times \sinh \gamma_1 l_{mi} + \dot{I}_{f1} Z_{C1} \times \sinh \gamma_1 l_{fi} \\ \dot{I}_{i1} = -\frac{\dot{V}_{m1}}{Z_{C1}} \times \sinh \gamma_1 l_{mi} + \dot{I}_{m1} \times \cosh \gamma_1 l_{mi} - \dot{I}_{f1} \times \cosh \gamma_1 l_{fi} \end{cases} \quad (7)$$

Additionally, $\dot{V}_{i1}$ and $\dot{I}_{i1}$ can be calculated via the positive sequence voltage and current at joint j ($\dot{V}_{j1}$, $\dot{I}_{j1}$) calculated by (2).

$$\begin{cases} \dot{V}_{i1} = \dot{V}_{j1} \times \cosh \gamma_2 l_{ij} - \dot{I}_{j1} Z_{C2} \times \sinh \gamma_2 l_{ij} \\ \dot{I}_{i1} = -\frac{\dot{V}_{j1}}{Z_{C2}} \times \sinh \gamma_2 l_{ij} + \dot{I}_{j1} \times \cosh \gamma_2 l_{ij} \end{cases} \quad (8)$$

where Z_{C2} and γ_2 are, respectively, the positive sequence natural impedance and the positive sequence propagation constant of the GIL. It can be expressed as

$$\begin{cases} Z_{C2} = R_2 + jX_2 \\ \gamma_2 = \alpha_2 + j\beta_2 \end{cases} \quad (9)$$

where R_2 , X_2 , α_2 and β_2 are the real and imaginary parts of the positive sequence natural impedance and the positive sequence propagation constant correspondingly.

Two (10) and (11) are obtained by transposing (6) and (7).

$$\dot{I}_{f1} Z_{C1} \times \sinh \gamma_1 l_{fi} = \dot{V}_{j1} \times \cosh \gamma_2 l_{ij} - \dot{I}_{j1} Z_{C2} \times \sinh \gamma_2 l_{ij} - \dot{V}_{m1} \times \cosh \gamma_1 l_{mi} + \dot{I}_{m1} Z_{C1} \times \sinh \gamma_1 l_{mi} \quad (10)$$

$$\begin{aligned} \dot{I}_{f1} \cosh \gamma_1 l_{fi} = & -\frac{\dot{V}_{j1}}{Z_{C2}} \times \sinh \gamma_2 l_{ij} + \dot{I}_{j1} \times \cosh \gamma_2 l_{ij} \\ & -\frac{\dot{V}_{m1}}{Z_{C1}} \times \sinh \gamma_1 l_{mi} + \dot{I}_{m1} \times \cosh \gamma_1 l_{mi} \end{aligned} \quad (11)$$

In order to eliminate the positive sequence current at fault point f, performing a division with (10) and (11). (see (12)) It can be seen from (12) that the equation is a complex function about the distance from fault point f to joint i (l_{fi}). Thus, the fault point can be located when a fault occurred on overhead line 1 on the basis of (12).

When a fault occurred on GIL, the positive sequence model of hybrid segment 1 is illustrated in Fig. 3.

Using the same analysis method as fault located on overhead line 1, the relationship between the distance from fault point f to joint i (l_{fi}) and the electrical quantities of point m and joint j can be deduced as (13). (see (13)) It can be seen from (12) and (13) that the right side of the two equations are identical and the left side are

$$\begin{aligned} f(l_{fi}) &= Z_{C1} \tanh \gamma_1 l_{fi} \\ &= \frac{\dot{V}_{j1} \times \cosh \gamma_2 l_{ij} - \dot{I}_{j1} Z_{C2} \times \sinh \gamma_2 l_{ij} - \dot{V}_{m1} \times \cosh \gamma_1 l_{mi} + \dot{I}_{m1} Z_{C1} \times \sinh \gamma_1 l_{mi}}{-(\dot{V}_{j1}/Z_{C2}) \times \sinh \gamma_2 l_{ij} + \dot{I}_{j1} \times \cosh \gamma_2 l_{ij} - (\dot{V}_{m1}/Z_{C1}) \times \sinh \gamma_1 l_{mi} + \dot{I}_{m1} \times \cosh \gamma_1 l_{mi}} \end{aligned} \quad (12)$$

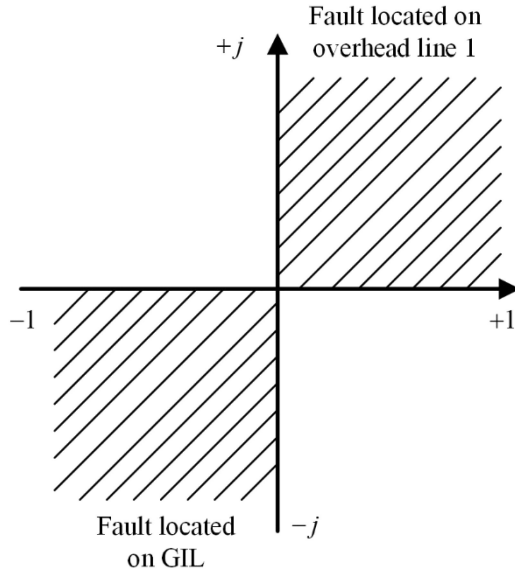


Fig. 4 Section identification function of hybrid segment 1 on complex plane

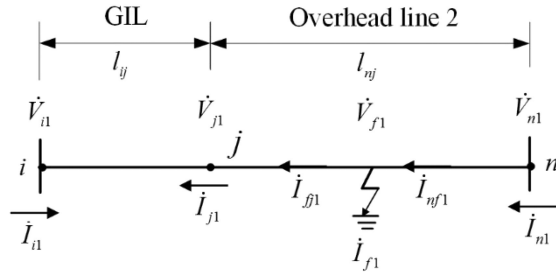


Fig. 5 Positive sequence model of hybrid segment 2

two complex functions about the distance l_{fi} . Thus, the fault point can be located when a fault occurred on overhead line 1 or on GIL on the basis of (12). By rearranging in accordance with the sequence of the real and imaginary parts, the left side of (12) and (13) can be rewritten as (14) and (15).

$$Z_{C1} \tanh \gamma_1 l_{fi} = R_1 A_1 - X_1 R_1 + j(R_1 B_1 + X_1 A_1) \quad (14)$$

$$Z_{C2} \tanh \gamma_2 l_{fi} = R_2 A_2 - X_2 B_2 + j(R_2 B_2 + X_2 A_2) \quad (15)$$

where A_n and B_n ($n = 1, 2$) are, respectively, illustrated as (16).

$$\begin{cases} A_n = \frac{\tanh \alpha_n l_{fi} \times (1 + \tan^2 \beta_n l_{fi})}{1 + \tanh^2 \alpha_n l_{fi} \times \tan^2 \beta_n l_{fi}} \\ B_n = \frac{\tan \beta_n l_{fi} \times (1 + \tanh^2 \alpha_n l_{fi})}{1 + \tanh^2 \alpha_n l_{fi} \times \tan^2 \beta_n l_{fi}} \end{cases} \quad (16)$$

A_n and B_n are two odd-functions about the distance l_{fi} , so the real and imaginary parts of (14) and (15) are the odd-functions about the distance l_{fi} . It is assumed that the distance l_{fi} is, respectively, positive or negative when fault occurred on overhead line 1 or GIL,

with joint i as the reference point. The section identification characteristics of (12) on complex plane is shown as Fig. 4.

It is noted that, in Fig. 4, the real and imaginary parts of the fault section identification function of hybrid segment 1 are positive when fault occurred on overhead line 1, so it located on the first quadrant of the complex plane. Conversely, the results are negative when fault occurred on GIL and it located on the third quadrant.

The positive sequence model of hybrid segment 2 is illustrated in Fig. 5.

Using the same analysis method as hybrid segment 1, the relationship between the distance from fault point f to joint j (l_{fj}) and the electrical quantities of point m and joint j can be deduced as (17). (see (17)) It can be seen from (17) that the left side is a complex function about the distance l_{fj} , with the real and imaginary parts demonstrated as the odd-functions. Thus, assuming that the distance l_{fj} is, respectively, positive or negative when fault occurred on overhead line 2 or GIL, with joint j as the reference point. The section identification characteristics of (17) on complex plane is shown in Fig. 6.

It is noted that the real and imaginary parts of the fault section identification function of hybrid segment 2 are positive when fault occurred on overhead line 2, so it located on the first quadrant of the complex plane. Conversely, the results are negative when fault occurred on GIL and it located on the third quadrant.

3 Fault section identification method

It can be seen from Section 2 that the real and imaginary parts of the two fault section identification functions show different characteristics when faults occurred on different sections of the hybrid line. So, the fault section can be identified with the results of the section identification functions.

When fault occurred on GIL, the positive voltages and currents at joint i and joint j calculated by (1) and (2) are correct. The real and imaginary parts of the fault section identification functions shown in (12) and (17) are negative simultaneously in this case. Thus, the method could determine that fault located on GIL, otherwise the fault located on overhead line.

The curves of the real and imaginary parts of the function $f(l_{fi}) = Z_{C1} \tanh \gamma_1 l_{fi}$ are shown as Figs. 7 and 8.

It can be seen from Figs. 7 and 8 that the real and imaginary parts of the curves are symmetrical about the reference point, but the amplitude of the real part curve is smaller than that in the imaginary part curve. Thus, the imaginary parts of the fault section identification functions are adopted for the sake of greater performance. The flow chart of the fault section identification method is illustrated as Fig. 9.

4 Simulation test and error analysis

PSCAD-based simulations are carried out, and the accuracy of the fault section identification method is tested. The UHV GIL-overhead hybrid line model is built in this software, with overhead line 1 length of 200 km, GIL length of 60 km, and overhead line 2 length of 85 km correspondingly.

The per-unit length electrical parameters of the overhead line and the GIL are listed in Table 1.

The fault is carried out for each 5 km in the UHV GIL-overhead hybrid line model, and the electrical quantities in two terminals are brought into the fault section identification function to plot the

$$\begin{aligned} f'(l_{fi}) &= Z_{C2} \tanh \gamma_2 l_{fi} \\ &= \frac{\dot{V}_{mi} \times \cosh \gamma_1 l_{mi} - \dot{I}_{mi} Z_{C1} \times \sinh \gamma_1 l_{mi} - \dot{V}_{j1} \times \cosh \gamma_2 l_{ij} + \dot{I}_{j1} Z_{C2} \times \sinh \gamma_2 l_{ij}}{-(\dot{V}_{mi}/Z_{C1}) \times \sinh \gamma_1 l_{mi} + \dot{I}_{mi} \times \cosh \gamma_1 l_{mi} - (\dot{V}_{j1}/Z_{C2}) \times \sinh \gamma_2 l_{ij} + \dot{I}_{j1} \times \cosh \gamma_2 l_{ij}} \end{aligned} \quad (13)$$

$$\begin{aligned} f(l_{fj}) &= Z_{C1} \tanh \gamma_1 l_{fj} \\ &= \frac{\dot{V}_{i1} \times \cosh \gamma_2 l_{ij} - \dot{I}_{i1} Z_{C2} \times \sinh \gamma_2 l_{ij} - \dot{V}_{n1} \times \cosh \gamma_1 l_{nj} + \dot{I}_{n1} Z_{C1} \times \sinh \gamma_1 l_{nj}}{-(\dot{V}_{i1}/Z_{C2}) \times \sinh \gamma_2 l_{ij} + \dot{I}_{i1} \times \cosh \gamma_2 l_{ij} - (\dot{V}_{n1}/Z_{C1}) \times \sinh \gamma_1 l_{nj} + \dot{I}_{n1} \times \cosh \gamma_1 l_{nj}} \end{aligned} \quad (17)$$

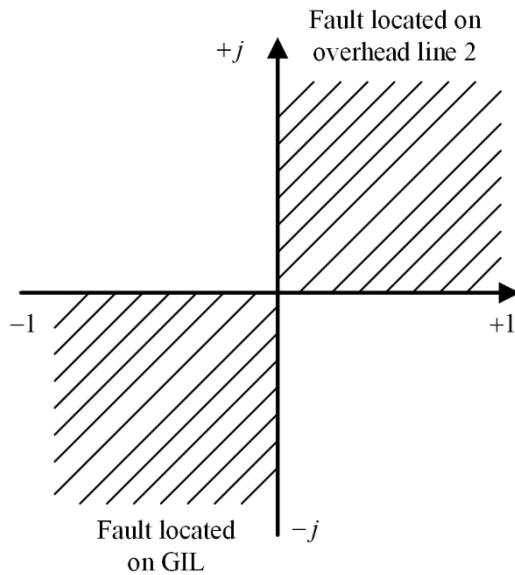


Fig. 6 Section identification function of hybrid segment 2 on complex plane

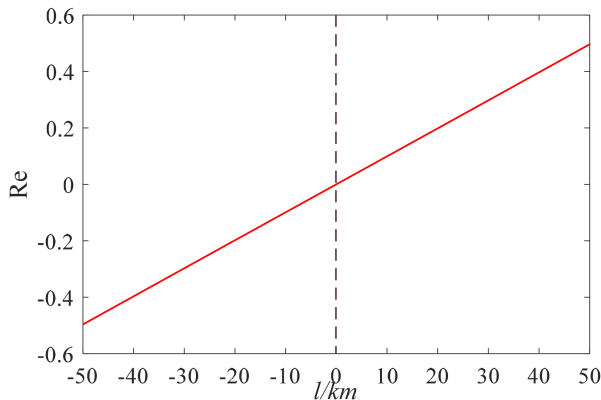


Fig. 7 Real part curve of $f(l_f)$ in different fault positions

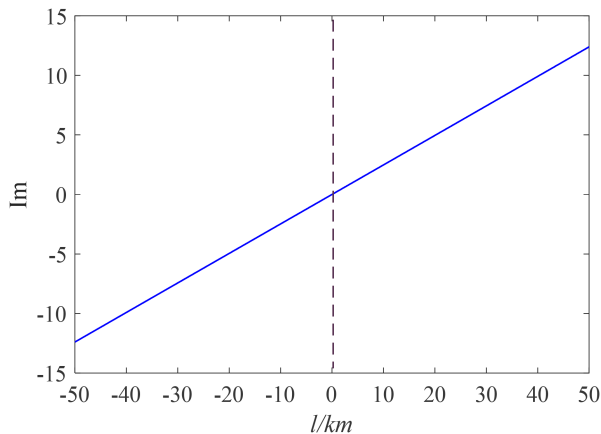


Fig. 8 Imaginary part curve of $f(l_f)$ in different fault positions

distribution characteristics on the complex plane which are shown in Fig. 10.

It can be seen from Fig. 10 that the dots located on the first quadrant of the complex plane when fault occurred on overhead line 1 or overhead line 2, conversely, the dots located on the third quadrant when fault occurred on GIL, so verify the validity of the fault section identification functions.

Different fault types include three phases to ground (K1), single phase to ground (K2), and double phases to ground (K3) are carried out for different fault locations on GIL at 201 km (head end of the GIL) and at 259 km (tail end of the GIL). Then, the results

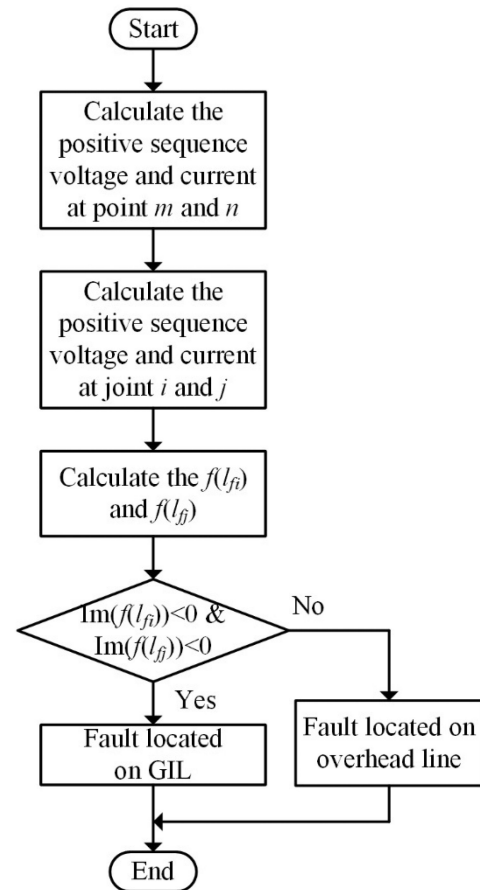


Fig. 9 Flow chart of fault section identification method

Table 1 Electrical parameters of overhead line and GIL

	Parameter	Positive sequence	Zero sequence
overhead line	$R \Omega/\text{km}$	9.9081×10^{-3}	1.8160×10^{-1}
	$L \text{ mH}/\text{km}$	0.7884	2.4640
	$C \mu\text{F}/\text{km}$	0.0145	7.2454×10^{-3}
GIL	$R \Omega/\text{km}$	2.7109×10^{-3}	1.5116×10^{-1}
	$L \text{ mH}/\text{km}$	0.2612	4.4127
	$C \mu\text{F}/\text{km}$	0.0313	0.0307

can be calculated by the fault section identification method and are shown in Table 2.

It can be seen from Table 2 that the imaginary parts of the fault section identification functions are negative when fault occurred on the head end and the tail end of GIL, namely, the fault located on GIL. Thus, the effectiveness of this method has been verified.

To test the accuracy of this method under different fault conditions, change the location of the fault point towards joint i or j . The results can be obtained when the imaginary parts of the fault section identification functions are positive. They are shown in Table 3.

In Table 3, the distances in first row are zero indicated that the fault located on GIL when fault type of three phases to ground. Additionally, the errors are produced when fault types of single phase to ground and double phases to ground because of the deviation between the parameters used by algorithm and the parameters of the model.

The factors affecting the accuracy of the algorithm in practice are analysed and listed as follows:

- The line parameters are affected by the environment and the accuracy of the algorithm will be reduced. Therefore, the line parameters online calculation methods can be adopted to ensure the accuracy of the line parameters.

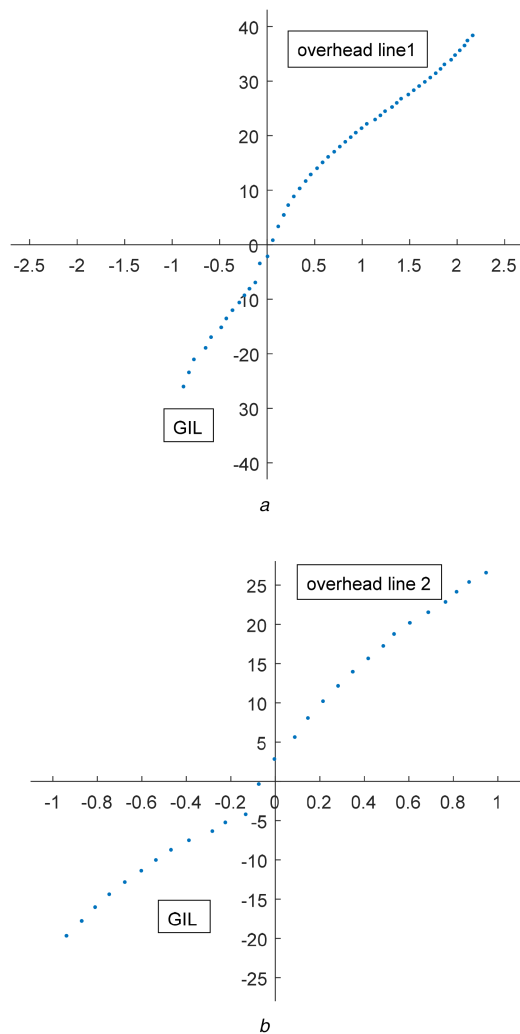


Fig. 10 Distribution characteristics of the fault section identification functions

Table 2 Results of fault section identification functions

Fault point, km	Fault type	$\text{Im}(f(I_f))$	$\text{Re}(f(I_f))$	Fault location
201	K1	-3.4325	-22.2210	GIL
	K2	-15.2256	-24.3154	GIL
	K3	-6.8758	-27.2974	GIL
259	K1	-25.3564	-0.7853	GIL
	K2	-30.4357	-7.3310	GIL
	K3	-26.3525	-12.5871	GIL

Table 3 Accuracy of fault section identification method

Fault type	Distance from i , m	Distance from j , m
K1	0	0
K2	780	460
K3	30	550

- The data in two terminals are not synchronised because of the time delay of the information transfer. Thus, a certain number of

out-of-sync detection and correction methods can be applied to correct double-ended data.

- The voltages and currents contain harmonic components after a fault, which will affect the accuracy of the algorithm. A certain filter algorithm can be adopted to eliminate the harmonic components.

5 Conclusion

This paper analysed the electrical characteristics of different sections of the UHV GIL-overhead hybrid line and established a fault section identification function. According to the characteristics of the complex plane derived from the function, this paper proposed a fault section identification method for the UHV GIL-overhead hybrid line. Some conclusions are as follows:

The real and imaginary parts of the fault section identification function are two odd-functions about the fault distance and the results show positive or negative when fault occurred on overhead line or GIL.

The fault section identification method is based on the positive sequence circuit of the GIL-overhead hybrid line, so this method can identify the fault section no matter what type of fault occurred.

Compared with the traditional fault location method based on traveling wave or failure analysis, the method based on the fault section identification functions shows clear physical meaning and high accuracy in fault location.

6 Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant no. 51677125 and by the Science and Technology Project of the State Grid Corporation of China: Research of Relay Protection Technology for UHV GIL-overhead Hybrid Transmission Line.

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