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To cite this article: Xu-ming Tang *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **486** 012099

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A New Location Method of Faulty Segment for Hybrid Transmission Lines Based on Transient Travelling Wave Analysis

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Abstract. The paper proposes a new location method of faulty segment for hybrid transmission lines combined with overhead line and cable. Conventional location method of faulty segment identify faulty segment through position calculation of fault point. However, affected by error, the fault at cable-overhead line joint is hard to be identified. In this approach, faulty segment is identified through characteristics comparison of transient travelling wave under different condition. Compared with situation that fault occurs on overhead line, if fault occurs in cable, there is an additional impedance discontinuity in cable. Thus, the amplitude and wave of various reflected wave will change significantly. The proposed method extracts various reflected waves based on time windows and polarity. It makes use of the relative amplitude and time difference between first travelling wave and secondary reflected wave of cable-overhead line joint as criterion of faulty segment location. To verify its effectiveness, fault simulations based on EMTDC are performed; the simulation results reveal that the proposed method can correctly identify the faulty segment for hybrid transmission lines.

1. Introduction

Hybrid transmission lines combined with overhead line and underground cable is widely used in power grid. Hybrid lines put forward new requirements to relay protection and auto reclosure. Since the fault occurred at cable segment is mostly permanent, the enclosing of breaker may cause secondary impact to power grid and cable. To ensure the safety, some auto-reclosure used on hybrid lines with long distance cable are not put in, and the temporary failure will cause long-term power outages [1, 2]. From the perspective of improving the reliability of power grid, relay protection device should have the function of fault segment location. Auto-reclosure put in when the fault point locates at overhead line, but if cable fault, auto-reclosure should be locked.

Presently, many studies have been carried out for faulty segment location on hybrid transmission lines. AREVA proposed the scheme which identify faulty segment through impedance matching of two section distance protection in 1998. ABB proposed faulty segment scheme which judged faulty segment by differential protection, but the scheme need current transformer and communication link between the both ends of cable. The methods based on travelling wave fault location are another research direction recently. In [3], fault segment location method based on double-ended travelling-



wave location is discussed. In [4], a method extracts phase difference of voltage and current through wavelet transform, and then input phase difference to ANN neural network as feature to figure out faulty segment. [5] presents a new approach for fault location in the high-voltage power transmission line using SVM and frequency characteristics of the measured one terminal voltage and current transient signals of the system.

Nevertheless, due to various factors, the above methods are seldom applied. First of all, for medium voltage and low voltage hybrid transmission lines, the method of faulty segment location which need double-ended data or signal transformers is basically infeasible on site. Secondly, whatever travelling-wave method [3-17], the method based on distance protection or the methods based on comparison of power frequency signal, location error is inevitable. Hence, existing methods are difficult to identify the faults near cable-overhead joint reliably. However, the joint of cable and overhead (abbreviated as joint) is the highest failure section in hybrid line.

A method of faulty segment location for hybrid transmission lines based on single-ended data is proposed in paper. It uses the characteristics difference of the secondary reflected wave to identify faulty segment. From the perspective of on-site implementation, the method based on single-ended data is easier to realize, and it may has better real-time performance.

2. Transient process analysis of fault occur on hybrid line

2.1. Process analysis of transient travelling wave

The most common structure of hybrid transmission lines whose voltage is higher than 35kV is, the cable locating at the exit of the substation, the overhead line after the cable. Therefore, this paper focuses on cable in the front section of hybrid line. For those cables locating at the middle of the hybrid lines, the principle of fault location is similar.

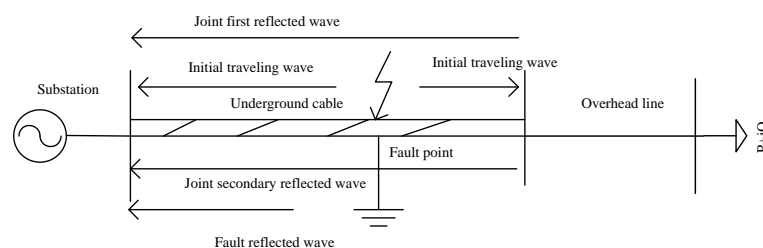


Figure 1. Wave process when fault occur in cable

When fault occurred in the cable of hybrid transmission lines, the transient travelling wave process is shown in Figure 1. After the failure, the initial fault travelling wave propagates to both directions of line. The initial travelling wave reaches the joint, it will reflect at the point. The reflected wave is named as first reflected wave of the joint (abbreviated as joint reflected wave). After that, the initial fault travelling wave reaches the substation bus end and reflects; the reflected wave returns to the fault point and reflects again here, which is the reflected wave of fault point (abbreviated as fault reflected wave). When reflected wave from the bus reaches the joint through the fault point, it will reflect again at the point, this reflected wave is named as secondary reflected wave of the joint (abbreviated as joint secondary reflected wave).

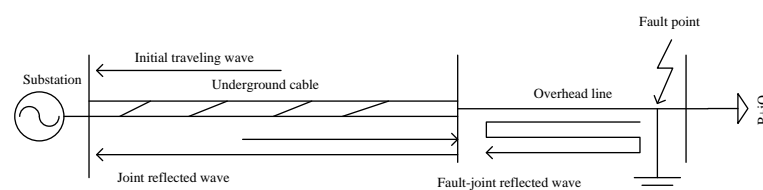


Figure 2. Wave process when fault occur in overhead line

When fault point is located in the overhead lines, the transient travelling wave process is shown in Figure 2. In this case, when the initial travelling wave reaches the joint, it will reflect at joint. And the reflected wave returns to the fault point and reflect at fault point again, which is fault-joint reflected

wave. Since the fault point locates in the overhead line, there is no joint reflected wave. The initial travelling wave will reflect back and forth between substation bus and joint, and the secondary reflected wave of the joint will generate in the process.

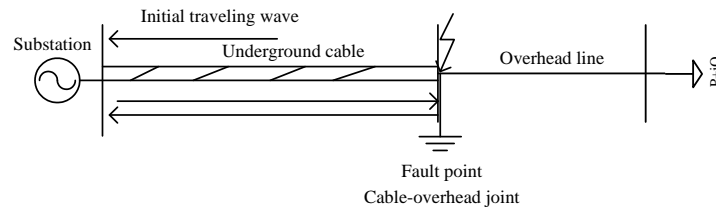


Figure 3. Wave process when fault occur on joint

When the fault point is located at the joint, the transient travelling wave process is shown in Figure 3. At this time, there is only one reflected wave in the timing window (assuming the cable length is L_1 , the cable wave velocity is v_1 , so the timing window is $2 \times L_1/v_1$), that is the fault point reflected wave and it is also the joint reflected wave at the same time.

Because the aim of faulty segment location is to assist the auto-reclosure decision on most occasions, the accurate position of fault point is not necessary in theory. Only judgement of whether there is a fault point in the cable or joint is needed. When the fault point locates at different segments of hybrid lines, the characteristics of reflected wave are different. Therefore, it is feasible to make out faulty segment based on transient characteristics

3.2. Characteristics analysis of reflected wave

- Fault occurring in cable

The amplitude and polarity of the travelling wave are decided by the characteristic impedance of discontinuity point. The characteristic impedance Z_{c1} of overhead lines is between 200 Ω and 400 Ω [18], and Z_{c2} of cables is between 50 Ω and 75 Ω , assuming the transition resistance is R_g , the refracted coefficient of different impedance discontinuity point is as follows:

(1) Voltage/current reflection coefficient at the joint is:

$$\beta_{i2} = -\beta_{u2} = \frac{Z_{c2} - Z_{c1}}{Z_{c1} + Z_{c2}} \quad (1)$$

(2) Voltage/current reflection coefficient at the fault point is:

$$\beta_{i1} = -\beta_{u1} = \frac{Z_{c2} - Z_{c2} // R_g}{Z_{c2} + Z_{c2} // R_g} \quad (2)$$

(3) At the substation bus end, if the number of branch connecting to the same bus is n ($n > 1$), the voltage/current reflection coefficient is:

$$\beta_{i0} = -\beta_{u0} \approx 1/(n-1) \quad (3)$$

(4) Voltage/current refraction coefficient at the fault point is:

$$\alpha_{u1} = \alpha_{i1} = \frac{2Z_{c2} // R_g}{Z_{c2} + Z_{c2} // R_g} \quad (4)$$

$Z_{c2} // R_g$ represents the parallel resistance of the fault resistance and characteristic impedance of cable. Assuming the initial amplitude of fault voltage/current travelling wave is u_f and i_f , respectively, the initial voltage/current travelling wave measured at the bus end is:

$$\begin{aligned} u_{f0} &= (1 - \beta_{u0}) u_f e^{-\gamma l} \\ i_{f0} &= (1 - \beta_{i0}) i_f e^{-\gamma l} \end{aligned} \quad (5)$$

The fault point voltage/current reflected waves (u_{f1} and i_{f1}) are:

$$\begin{aligned} u_{f1} &= \beta_{u0}\beta_{u1}(1-\beta_{u0})u_f e^{-2\gamma l} \\ i_{f1} &= \beta_{i0}\beta_{i1}(1-\beta_{i0})i_f e^{-2\gamma l} \end{aligned} \quad (6)$$

In formula 6, $e^{-\gamma l}$ is the signal attenuation per unit length, and γ is the attenuation coefficient. It can be known from the [19] that if the signal frequency is lower than 5MHz, the attenuation of the signal during the cable transmission process is basically below 0.005db/m. Therefore, when the length of cable is short, the reflected coefficient is the mainly influenced factor for amplitude of reflected wave. By ignoring the attenuation in propagation process, the initial travelling wave is made as the reference value. The relative value of the fault reflected wave can be normalized:

$$\begin{aligned} u_{xf1} &= \beta_{u0}\beta_{u1} \\ i_{xf0} &= \beta_{i0}\beta_{i1} \end{aligned} \quad (7)$$

The relative value of the joint reflected wave:

$$\begin{aligned} u_{xf2} &= -\alpha_{u1}\beta_{u2} \\ i_{xf2} &= \alpha_{i1}\beta_{i2} \end{aligned} \quad (8)$$

The relative value of the joint secondary reflected wave:

$$\begin{aligned} u'_{xf2} &= \alpha_{u1}\alpha_{u1}\beta_{u0}\beta_{u2} \\ i'_{xf2} &= \alpha_{i1}\alpha_{i1}\beta_{i0}\beta_{i2} \end{aligned} \quad (9)$$

According to equations 7, 8, and 9, it can be deduced that, after hybrid line fault occurs, since the characteristic impedance of the cable is less than the characteristic impedance of the overhead line, the joint secondary reflected waves is negative. At the same time, the fault reflected wave and the joint reflected wave are both positive. In addition, the polarity of the voltage/current reflected wave is basically the same, but the polarity of the voltage/current reflected wave is different in following case: the substation has other hybrid lines connecting to same bus, and the voltage/current reflected waves of joint in others hybrid lines are opposite in polarity. Therefore, it is more reasonable to calculate voltage and current simultaneously.

- Fault occurring in overhead line

When the fault point is located in the overhead line, compared with situation that the fault point lied in cable, the fault-joint reflected wave is added, and there is no joint reflected wave. The relative value of the fault-joint reflected wave is:

$$\begin{aligned} u_{xf1} &= \alpha_{u1}\beta_{u2}\beta_{u1} \\ i_{xf1} &= \alpha_{i1}\beta_{i2}\beta_{i1} \end{aligned} \quad (10)$$

At this time, the relative value of the secondary reflected wave of the joint is:

$$\begin{aligned} u'_{xf2} &= \beta_{u0}\beta_{u1} \\ i'_{xf2} &= \beta_{i0}\beta_{i1} \end{aligned} \quad (11)$$

Equation 11 shows that: when the fault point is located in the overhead line, the amplitude of the joint secondary reflected wave is independent of the faulty transition resistance, and just decided by the reflected coefficients of the substation bus and joint, they are fixed in theory.

- Fault occurring at joint.

When the fault point is located at the joint of the cable and overhead line, the amplitude of reflected wave at the fault point is:

$$\begin{aligned} u_{xf0} &= \beta_{u0}\beta_{u1} \\ i_{xf0} &= \beta_{i0}\beta_{i1} \end{aligned} \quad (12)$$

At this point, the reflected coefficient of the fault point (as well as joint) becomes:

$$\beta_{i1} = -\beta_{u1} = \frac{Z_{c2} - Z_{c1} // R_g}{Z_{c2} + Z_{c1} // R_g} \quad (13)$$

In Equation 13, $Z_{c1} // R_g$ represents the parallel impedance of the overhead line and the fault transition resistance. When $Z_{c1} // R_g$ is less than the characteristic impedance of the cable, the reflected

point of the fault point/joint is negative, while when $Z_{c1} // R_g$ is greater than the characteristic impedance of the cable, the polarity of fault/joint reflected wave becomes positive. Taking a typical cable characteristic impedance of 68 ohms and an overhead line impedance of 220Ω as an example, when the transition resistance R_g is greater than 94Ω , the polarity of the fault point/joint reflected wave changes.

- Principle of faulty segment location

When the fault point is located at different segments of the hybrid lines, the characteristics of different reflected waves are shown in Table 1. In the table, β_0 is the reflected coefficient of the substation bus, β_1 is the reflected coefficient of the joint, and α is the refractive coefficient of the fault point.

Table1. Characteristics of reflected waves

Faulty segment	Reflected wave type	Time difference	Amplitude	Polarity
Overhead line	Joint secondary reflected wave	T	$\beta_0\beta_1$	Positive
	fault-joint reflected wave	--	--	Negative
Underground cable	Joint secondary reflected wave	T	$\alpha\alpha\beta_0\beta_1$	Negative
	Fault reflected wave	$<T$	$1-\alpha$	Positive
	Joint reflected wave	$<T$	$\alpha\beta_1$	Positive
Joint	Joint secondary reflected wave	T	$\beta_0\beta'_1$	Negative
	Fault reflected wave	T	$\beta_0\beta'_1$	Negative

Note: The time difference is the arrival time difference between the reflected wave and the initial travelling wave.

It can be seen from Table1 that the time difference between the joint secondary reflected wave and the initial travelling wave is substantially constant, which is independent from the fault position, and its polarity is always negative. At the same time, other types of reflected waves, including the joint reflected wave and the fault reflected wave are positive. When the fault point is located at different segments, the amplitude of the joint secondary reflected wave will change significantly.

When the fault point is located in the overhead line, the amplitude of the joint secondary reflected wave is close to $\beta_0\beta_1$, where β_0 and β_1 are constant values, β_0 is decided by the number of branch lines connecting to the same bus, and β_1 is decided by the characteristic impedance of the cable and the overhead line, and its benchmark value is:

$$\beta_1 \approx (Z_{c1} - Z_{c2}) / (Z_{c1} + Z_{c2}) \quad (14)$$

When the fault point is located in the cable, the amplitude of the joint secondary reflected wave is approximately equal to $\alpha\alpha\beta_0\beta_1$, where α is related to the faulty transition resistance R_g . When the faulty transition resistance is $0 \leq R_g \leq 300\Omega$, $0 \leq \alpha \leq 0.89$, the amplitude of joint secondary reflected wave is generally less than $0.89 \times 0.89 \times \beta_0 \times \beta_1 \approx 0.8 \times \beta_0 \times \beta_1$.

When the fault point is located at the joint, the amplitude of the joint secondary reflected wave is close to $\beta_0\beta'_1$, and β'_1 is related to R_g . The smaller the R_g is, the smaller the β'_1 means. When R_g is 10Ω , $\beta'_1 \approx 0.22 \times \beta_1$. Considering that the fault occurred at joint is mostly metallic grounding or short circuit, the amplitude of the joint reflected wave should be significantly decreased in most cases.

It can be seen from the analysis that if fault occurs on the overhead line in hybrid line, the amplitude and time difference of the joint secondary reflected wave are substantially fixed. When the fault point is located at joint or the fault occurs in the cable, their common feature is that the amplitude of the joint secondary reflected wave decreases, and it drops below the normal value by 80% generally. Therefore, the amplitude of the joint secondary reflected wave can be used as identifying criterion of faulty segment.

3. Simulation analysis

3.1. Simulation model

The EMTDC simulation model is shown in Figure 4. The electrical configuration of simulation is from the Luohe substation in Huainan city, Anhui province, China. The voltage level of the system is 35kV, and the cable is a three-core XLPE one. The simulation model of the overhead line and the cable adopt the frequency-dependent model provided by EMTDC. The length of the cable is 1.3km, and the total length of the hybrid lines is 13.1km. In the overhead line, the velocity of travelling wave is about 290~298m, while in the cable, the velocity of travelling wave is about 150~165m/us [19], which is obtained from line parameters. The measurement point of voltage and current are set at the 35kV bus end, and the sampling rate is 10MHz.

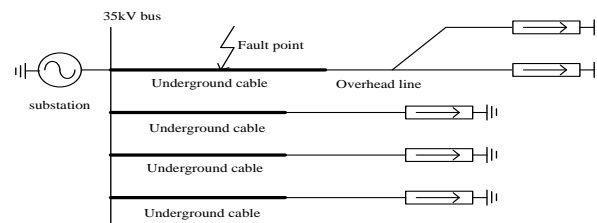


Figure 4. EMTDC simulation model

3.2. Simulation analysis

- Fault occurring in cable

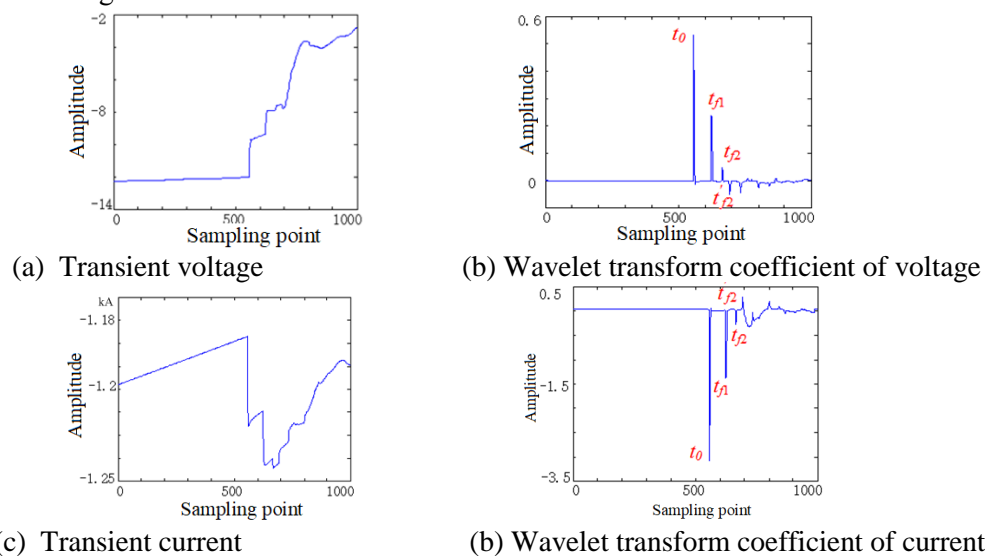


Figure 5. Simulation waveform when fault occurs in cable

Typical fault conditions in simulation are single-phase grounding fault and 1 Ω fault transition resistance. When fault occurs in cable and the fault point is 0.5km away from the joint, the transient voltage, current and wavelet transform coefficient are shown in Fig. 5. Assuming that the initial time is t_0 , the arrival time of the fault reflected wave is t_{f1} , the arrival time of joint reflected wave is t_{f2} , and the arrival time of the joint secondary reflected wave is t'_{f2} . The analysis data is shown in Table 2. When the fault is located in cable, various reflected wave have the following characters:

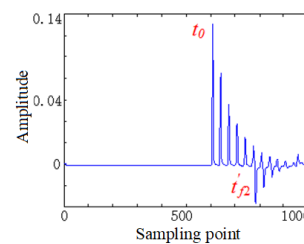
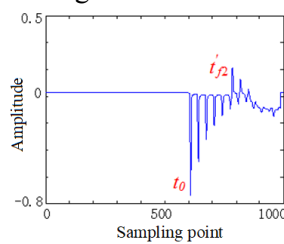
Compared with the initial travelling wave, the polarity of the joint secondary reflected wave is negative. The time difference between them is $(t'_{f2} - t_0) \times v \approx 2 \times L$.

The polarity of the fault reflected wave and the joint reflected wave are both positive. In the time domain, the two reflected waves above satisfy the condition: $(t_{f1} - t_0) \times v + (t_{f2} - t_0) \times v \approx 2 \times L$, which can be used as an auxiliary criterion.

Table2. Simulation result when fault occurs in cable

Arrival time	57	124	165	192
Relative value of voltage	1	0.445	0.084	-0.093
Type of travelling wave	Initial travelling wave	Joint reflected wave	Fault reflected wave	Joint secondary reflected wave
Arrival time	57	124	165	192
Relative value of current	1	0.448	0.086	-0.097
Type of travelling wave	Initial travelling wave	Joint reflected wave	Fault reflected wave	Joint secondary reflected wave

- Fault occurring in overhead line



(a) Wavelet transform coefficient of voltage (b) Wavelet transform coefficient of current

Figure 6. Simulation waveform when fault in overhead line

When the fault point is located in the overhead line, and it is 0.5km away from the joint, the waveform is shown in Figure 6. The various types of reflected waves have the following characteristics:

The character of the joint secondary reflected wave is similar to the former. Its polarity is negative, and the time difference between initial travelling wave is consistent with the cable length $(t_{j2} - t_0) \times v = L$. But its amplitude is relatively high, because there is no fault point in the cable. Thus, there is no refraction induced by the fault point. As shown in Table 3, the amplitude and polarity of the secondary reflected wave of the joint are independent of the position of the fault point or the transition resistance, and are basically fixed values $\beta_0 \times \beta_1$. In the simulation, the electrical parameters are as follows: $Z_{c1} \approx 68\Omega$, $Z_{c2} \approx 250\Omega$, $|\beta_1| \approx 0.572$, $|\beta_0| \approx 0.5$, $|\beta_0 \times \beta_1| \approx 0.286$.

Since the fault point is closer to the joint, the transient travelling wave will reflect multiple times between the joint and the fault point. But the fault-joint reflected waves do not affect the identification of the joint secondary reflected wave in simulation, because their polarity is positive.

Table3. Simulation result when fault occurs on overhead line

Arrival time	107	141	174	284
Relative value of voltage	1	0.659	0.434	-0.287
Type of travelling wave	Initial travelling wave	Fault-Joint reflected wave	Joint secondary reflected wave	
Arrival time	107	141	174	284
Relative value of current	1	0.655	0.428	-0.279
Type of travelling wave	Initial travelling wave	Fault-Joint reflected wave	Joint secondary reflected wave	

- Fault occurring at joint.



(a) Wavelet transform coefficient of voltage (b) Wavelet transform coefficient of current

Figure 7. Simulation waveform when fault occurs in cable

When the fault point is located at the joint, the transient waveform is shown in Figure 7, and the analysis data is shown in Table 4. At this time, there is only one reflected wave, which is joint secondary reflected wave, and the time difference between the reflected wave and the initial travelling wave is $(t'_{f2} - t_0) \times v \approx 2 \times L$.

Table4. Simulation data when fault occurs at joint

Arrival time	91	267
Relative value of voltage	1	-0.11673093
Type of travelling wave	Initial travelling wave	Joint secondary reflected wave
Arrival time	91	267
Relative value of current	1	-0.111911025
Type of travelling wave	Initial travelling wave	Joint secondary reflected wave

Compared with the fault point located in the overhead line, since the joint is the fault point and the equivalent impedance $Z_{c1} // R_g < Z_{c1}$, the amplitude of the joint secondary reflected wave is significantly reduced. The simulation results are consistent with the analysis in section 2.

It should be pointed out that if the fault point and the joint are in the same position, the fault transition resistance influences the joint secondary reflected wave greatly. The smaller the fault transition resistance is, the lower the amplitude of the joint secondary reflected wave becomes. As the fault transition resistance increases, the amplitude of the joint secondary reflected wave also increases correspondingly. For different fault transition resistances, the simulation data are shown in Table 5.

Table5. Amplitude of joint reflected wave when fault resistance is different

Fault resistance	Relative value of voltage	Relative value of current
1Ω	-0.1167	-0.1119
10Ω	-0.1335	-0.1298
90Ω	-0.2478	-0.2503

4. Flowchart of faulty segment location

The Flowchart of the faulty segment location based on the above principle is as follows:

- (1) Figuring out the arrival time of the initial travelling-wave front.
- (2) Extracting the timing window data after the initial wave front. When the cable length is L_1 , the wave velocity is v_1 , and the timing window is $2 \times L_1 / v_1$.
- (3) Identifying of the reflected wave. The joint secondary reflected wave can be identified in accordance with the polarity and the time difference between the initial travelling wave.
- (4) Judging whether the amplitude of the joint secondary reflected wave exceeds the limit. The setting value of limit is based on the bus reflected coefficient β_0 and the joint reflected coefficient β_1 . It can also be obtained from historical record sometimes. As mentioned above, when the fault point is located in the cable segment or the joint, the amplitude of the secondary reflected wave generally decreases below $0.8 \times \beta_0 \times \beta_1$ in most cases.

5. Summary

In this paper, the travelling wave process is analyzed after the fault occurs in hybrid line. When the fault point is located in different segments, there are significant differences in the polarity and amplitude of the various reflected wave, which can be utilized as basis of faulty segment location.

An approach of faulty segment location based on the characteristics analysis of reflected wave is proposed. It picks out joint secondary reflected through polarity and time-difference, and it identify faulty segment based on amplitude of joint secondary reflected wave. Compared with the existing methods, it can identify faulty segment without locating the accurate position of fault point. And the proposed approach is based on single-ended data, which is easier to be implemented on site. The proposed method is verified by simulation. The method is validated by simulation analysis in paper.

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