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Propagation Characteristics of Partial Discharge Pulse Current on 10kV Covered Conductor

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Abstract: *With the application of covered conductor in distribution overhead lines, the grounding and short circuit faults caused by foreign objects have been eliminated. But new partial discharge problem has appeared on the surface of the covered conductors around tower head. It may cause the single-phase grounding fault and affect the power supply reliability. To increase the reliability, status monitoring must be used to prevent the faults from beginning. Currently, the partial discharge on overhead lines is usually measured by coils. It utilizes pulse currents to check whether there is a partial discharge. However, it cannot be used in status monitoring as the propagation characteristics is not clear. This paper carried out a simulation study on the propagation characteristics. By constructing a simulation model of overhead lines with covered conductor by the distribution parameters, the initial pulse current amplitude and front time transformation rule in different transmission distance is obtained. Considering different conditions such as pulse current frequency domain (10~50MHz), covered conductor height (4.5~8.0m), covered conductors' phase spacing (0.6~1.0m), and conductor cross-sectional area (50~185mm^2), simulation results show that the amplitude attenuation rate is between 1.5% and 6.3% per 100m, and the front time growth rate is between 1.5% and 5.7% per 100m. The height of covered conductor has the greatest influence on the pulse current waveform transformation, and the main frequency of the pulse current takes the second place, while the difference between the phase spacing and the cross-sectional area has less than 1% influence on transformation.*

Keywords: *Distribution network, covered conductor, partial discharge, pulse current, propagation characteristics*

1. Introduction

Electricity supply network is an important support for social and economic development. The distribution network is responsible for connecting users to the power grid. With the gradual increase in the scale of power grid, the reliability of distribution network is attracting more and more attention. Data shows that the proportion of power outages due to distribution network equipment failures in 2019 accounted for 40.2% [1]. It suggests that the equipment status in distribution network has a great impact on the power supply reliability.

Figure 1: Partial Discharge Problem and Burned Insulation on Covered Conductors.

Through literature research and field inspection, we found that partial discharge problem occurs on the 10kV covered conductor around tower head. This problem has been found in both coastal area and inland area [2-7]. Thus, it has a wide distribution and heavy pollution is not the only cause. There are still other incentives to be analyzed. As showed in figure 1, these partial discharges will damage the insulation of covered conductor and may cause the single-phase grounding fault. Power supply reliability is then affected. Most covered conductors are fixed on insulators by binding wires around tower head. The partial discharge usually happens in the gap between covered conductor and binding wire. Without suitable detection devices, these discharges are hardly to be found during line petrol. Therefore, it difficult to determine the fault location and repair it in time. If partial discharge is allowed to develop on its own, it may also cause serious consequences such as single-phase ground faults and even fire. So, it must be dealt with in the early stage of partial discharge development.

In 2008, Finland researchers Hashmi and Lehtonen summarized the common methods of partial discharge detection in overhead lines [8]. They pointed out that the partial discharge pulse current in the distribution network can be measured by current transformers or Rogowski coils. As traditional current transformers have poor high-frequency response and can cause distortion of waveforms, high-bandwidth Rogowski coil is a better option. However, related researches are limited to detect the pulse current peak value through the coil, none of them uses the signals to carry out partial discharge pattern recognition [9-12]. In fact, the pulse current waveform carries various information of the partial discharge source. If the original pulse current waveform characteristics can be analyzed, the various information of the discharge source can be deduced [13]. As a result, equipment status evaluation cannot be carried out and extremely increases the reliably of distribution network.

In order to restore the original pulse current waveform from coil output, propagation characteristics of pulse current must be obtained. Therefore, this paper studies this characteristic when partial discharge occurs on the covered conductor around tower head by constructing the simulation model of the single-circuit overhead line with distributed parameters. The change rate of pulse current amplitude, front time, and tail time are analyzed. Different variables are discussed, such as the main frequency of the pulse current, the height of covered conductor, the sectional area of conductor, and the covered conductor distance between phases. Meanwhile, based on using the coil to measure the pulse current, the feasibility of the partial discharge detection on 10kV overhead covered conductor is discussed. This paper provides support of restoring the original pulse current waveform, and assistance of distribution network covered conductor status evaluation based on pulse current characteristics.

2. Simulation Model

Software ATP-EMPT is used to build simulation model in this paper. The structure of simulated distribution line is showed in figure 2. Block LCC represents overhead line. In order to measure the travelling waveform in different distances, the overhead line is divided into several sections and 11 measurement points are set.

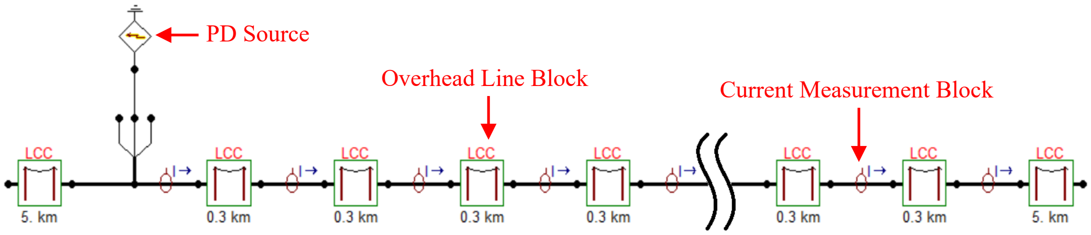


Figure 2: Simulation Model Circuit.

2.1. Line Model

The equivalent circuit of overhead line is by block LCC. In this block, model JMarti is selected in this paper as it is the most common used model in transient process analysis. It is suitable for analyzing the long-distance propagation characteristics of pulse current [14-16]. Parameter setup dialog of LCC block is showed in figure 3. It can be seen that overhead line parameters can be set freely, such as length, height, phase distance, react, and so on. Therefore, by changing these parameters, different structure of overhead lines can be simulated. Meanwhile, in this paper, the frequency of JMarti matrix is set to 30MHz to meet the frequency of partial discharge pulse current.

2.2. PD Source

According to the pulse current we measured in our experiment platform in our laboratory, the pulse current generated in distribution network tower head matches the double exponential pulse form [1]. Therefore, it can be fitted by equation (1) below.

$$i(t) = K \times (e^{A\times t} - e^{B\times t}) \tag{1}$$

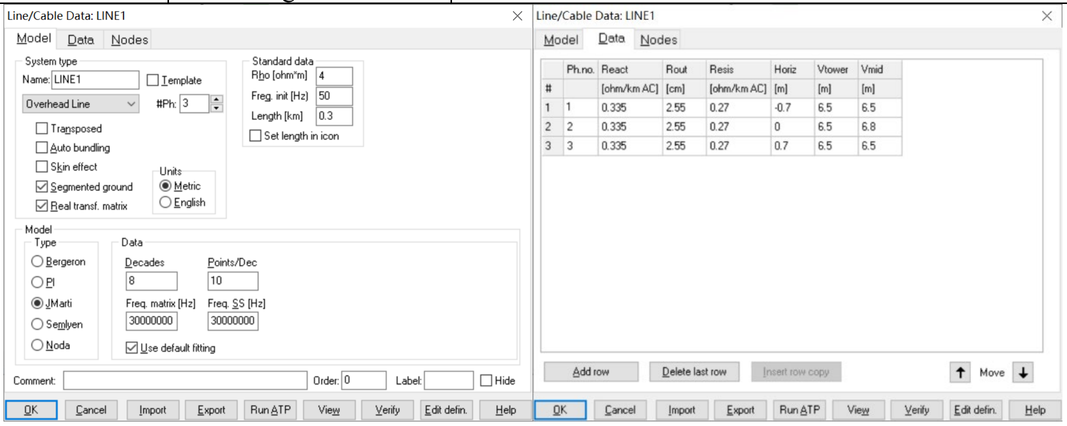
In this case, block Surge in ATP-EMPT can be used as PD source. A typical pulse current waveform and parameter setup of block Surge are showed in Figure 4. By changing parameters K, A, and B, different pulse currents can be simulated.

2.3. Simulation Variables

The frequency of pulse current is in the level of Mega Hz. Therefore, the distribution parameters of overhead covered conductor will affect propagation characteristics. Both of frequency of pulse current and the structure of overhead lines must be considered. According to the measured pulse currents and distribution overhead line design code [1], the variable ranges are listed in table 1 above. The default parameters (i.e., control group) are: 30MHz pulse current, 6.5m tower, 0.7m phase distance, and 120mm^2 covered conductor.

Table 1: Simulation Variables.

Variable	PD Source	Overhead line height	Overhead line phase distance	Overhead line sectional area
Range	10MHz ~ 55MHz	4.5m ~ 8.0m	0.6m ~ 1.0m	50mm^2 ~ 185mm^2
Adjustment Method	Changing parameters in Surge block	Changing parameters in LCC block		


Line/Cable Data: LINE1

Model tab:

System type
Name: LINE1 ☐ Template
Overhead Line #Ph: 3
☐ Transposed
☐ Auto bundling
☐ Skin effect
☑ Segmented ground
☑ Real transf. matrix

Units: ● Metric ○ English

Standard data
Rho [ohm*m]: 4
Freq. init [Hz]: 50
Length [km]: 0.3
☐ Set length in icon

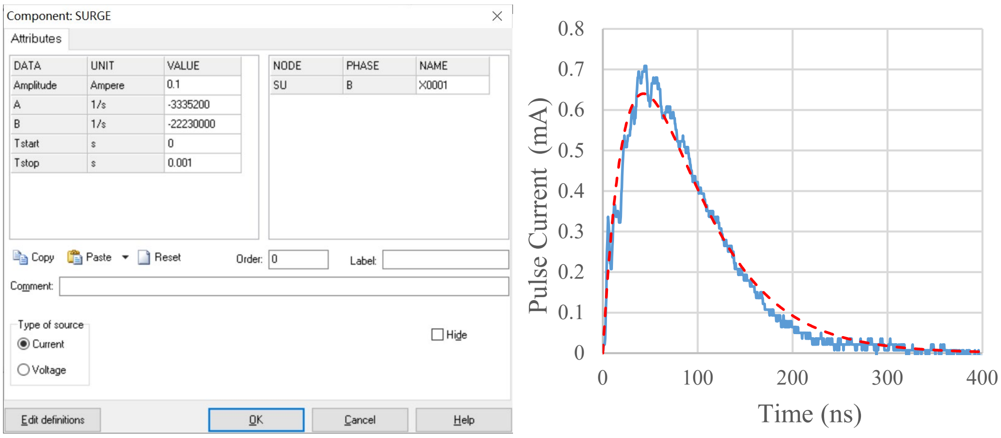
Model
Type: ○ Bergeron ○ PI ● JMarti ○ Semlyen ○ Noda
Data
Decades: 8
Points/Dec: 10
Freq. matrix [Hz]: 30000000
Freq. SS [Hz]: 30000000
☑ Use default fitting

Comment:
Order: 0
Label:
☐ Hide

Data tab:

	Ph.no.	React	Rout	Resis	Horiz	Vtower	Vmid
#		[ohm/km AC]	[cm]	[ohm/km AC]	[m]	[m]	[m]
1	1	0.335	2.55	0.27	-0.7	6.5	6.5
2	2	0.335	2.55	0.27	0	6.5	6.8
3	3	0.335	2.55	0.27	0.7	6.5	6.5

Figure 3: Parameter Settings in LCC Block.


Component: SURGE

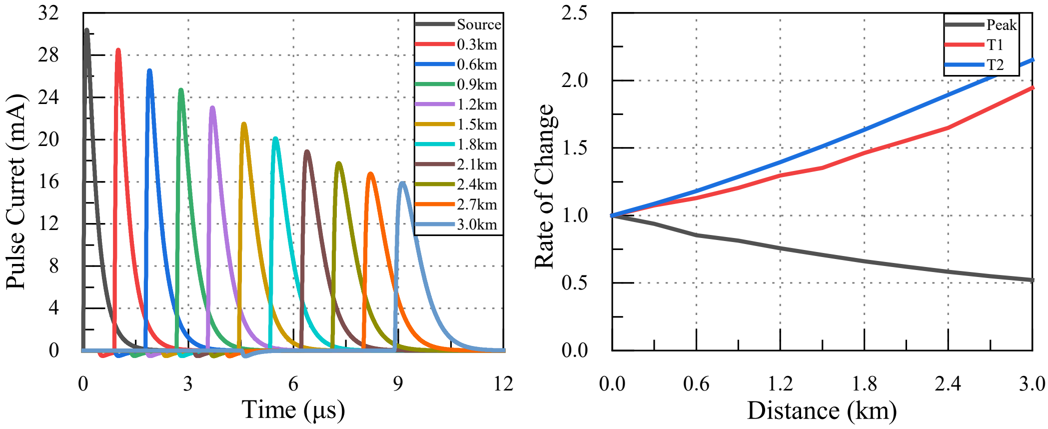
Attributes

DATA	UNIT	VALUE
Amplitude	Ampere	0.1
A	1/s	-3335200
B	1/s	-22230000
Tstart	s	0
Tstop	s	0.001

NODE	PHASE	NAME
SU	B	X0001

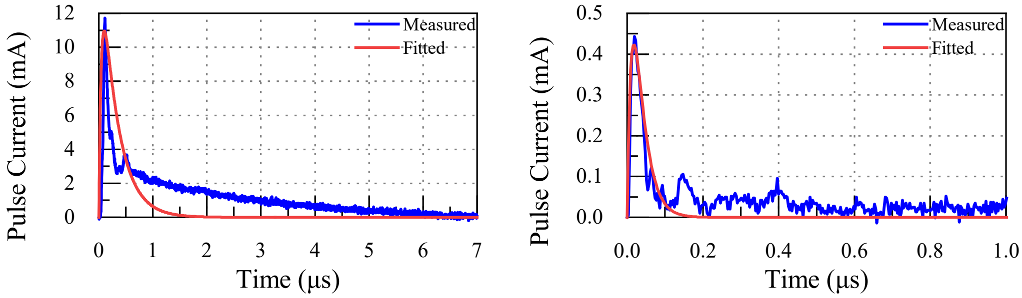
Order: 0
Label:
Comment:
Type of source: ● Current ○ Voltage
☐ Hide

Figure 4: Surge Block and Typical Pulse Current [1].



(a) Pulse Current Waveforms *(b) Change Rate of Waveform Parameters*

Figure 5: Simulation Results with Default Parameters.



(a) 15MHz Pulse Current *(b) 30MHz Pulse Current*

Figure 6: Different Pulse Currents of Partial Discharge in Tower Head.

3. Simulation Results and Discuss

3.1. Analysis Method

The left image in figure 5 illustrates the pulse current waveform in each measurement block with default parameters. For each pulse current waveform, its peak I_p, front time T_1 and tail time T_2 can be calculated based on standard IEC-62475.

By comparing these three parameters with PD source, we can obtain their change rates versus propagation distance. In this case, the change rate of 1 represents the measured waveform is as the same as PD source. The greater the deviation of the value from 1, the greater the difference in the waveform. For example, the right image of figure 5 shows clearly that the peak of pulse current is gradually decreased, while the front and tail time are gradually increased. It is obviously that these change rates represent the propagation characteristics of partial discharge pulse current.

3.2. Simulation Results with Different Pulse Current

Equation (1) represents the pulse currents in this paper. There are three parameters in it, which are the amplitude coefficient *K*, ionic current coefficient *A*, and electron current coefficient *B*. According to our test result in experiment platform, the frequency of pulse current varies from 15Mhz to 55MHz [1]. Figure 6 illustrate two measured pulse currents of different main frequencies. The front time of two pulse currents are 68ns and 8ns respectively, while the tail time are 154ns and 42ns respectively. These two pulse currents can be fitted as equation (2).

$$\begin{aligned} i_1(t) &= A_1 \times (e^{-3.34t} - e^{-22.23t}) \\ i_2(t) &= A_2 \times (e^{-39.71t} - e^{-76.06t}) \end{aligned} \tag{2}$$

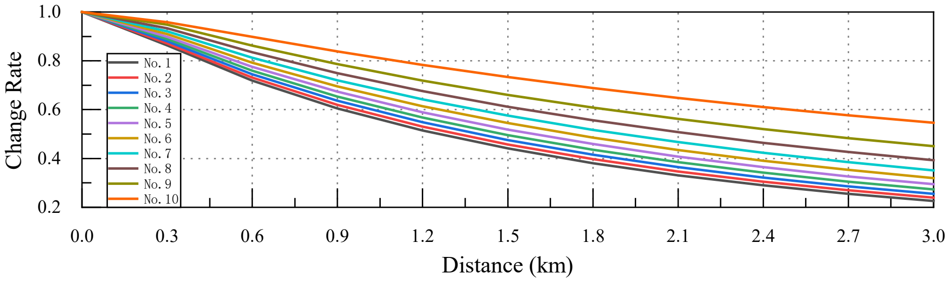
, where A_1 and A_2 are the amplitude coefficient of pulse current.

In order to analyze the how pulse current pattern affects propagation characteristic, different pulse current sources are simulated based on these two real waveforms. By using the parameters in equation (2) as minimum and maximum value, Surge block setting list can be obtained as showed in table 2. The parameters of No.2 to No. 9 are calculated by linear interpolation.

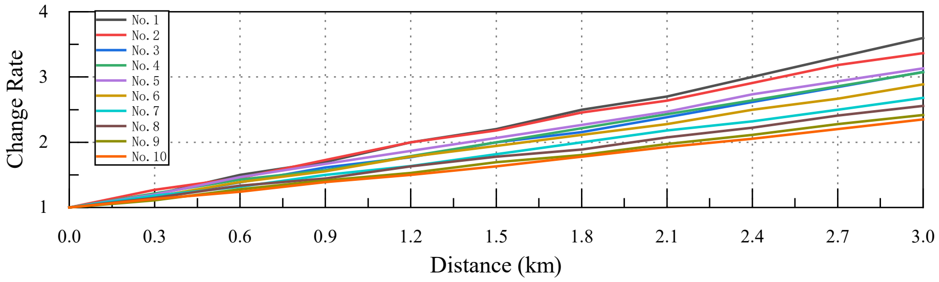
Figure 7 illustrates the simulation results of change rates with different PD sources. In all circumstances, the amplitudes decrease while front and tail times increases with the propagation distance. Meanwhile, it can be argued that with the decrease of the pulse current frequency, all three change rates of the amplitude are getting close to 1. In other words, the variation degree of waveform patterns is decreased together with the pulse current frequency. Under the condition of the single-circuit overhead line, high frequency pulse current decays faster during propagation. Its change rate of amplitude can reach up to 3.3% per 100m. For the low frequency pulse current, this change rate is about 2.0%/100m.

Table 2: Pulse Current Source Parameters.

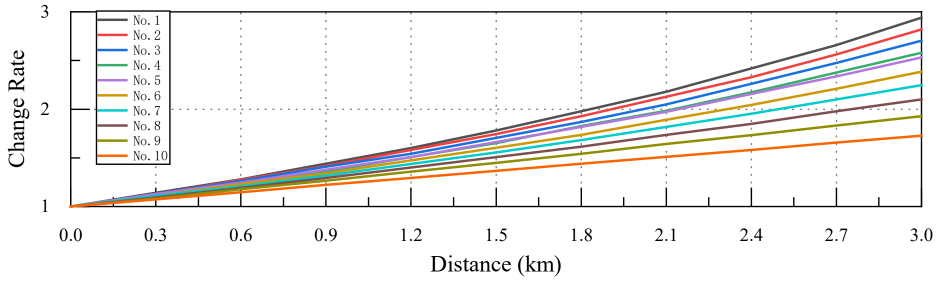
No.	1	2	3	4	5	6	7	8	9	10
K	1.80	3.60	5.40	7.21	9.01	10.81	12.61	14.42	16.22	18.02
A	39.71	35.67	31.63	27.59	23.54	19.50	15.46	11.42	7.38	3.34
B	76.06	70.08	64.10	58.12	52.14	46.15	40.17	34.19	28.21	22.23
Frequency (MHz)	<10	<15	<20	<25	<30	<35	<40	<45	<50	<55



(a) Amplitude Change Rate with Propagation Distance



(b) Front Time Change Rate with Propagation Distance



(c) Tail Time Change Rate with Propagation Distance

Figure 7: Pulse Current Propagation Characteristics of Different Pulse Current Frequencies.

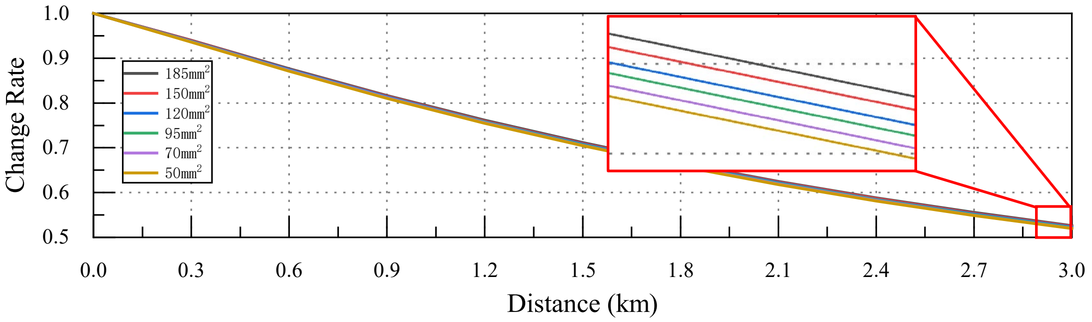
3.3. Simulation Results with Different Conductor Section

There are six commonly used covered conductors. Their parameters are listed in table 3. By entering the values of different conductor sections and default parameters into block LCC, simulation results showed in figure 8 are obtained.

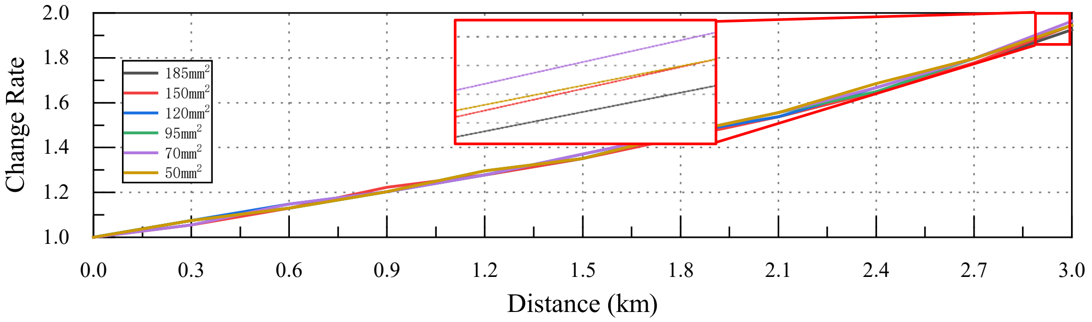
According to figure 8, it can be argued that the amplitudes decrease while front and tail times increases with the propagation distance. The variation degree of waveform patterns is decreased together with the increase of covered conductor section. It is worth to mention that the conductor section has little effect on the propagation characteristic. The difference of change rate values is only at most 2% between 50mm^2 and 180mm^2 covered conductors.

Table 3: Covered Conductor Parameters of Different Sections.

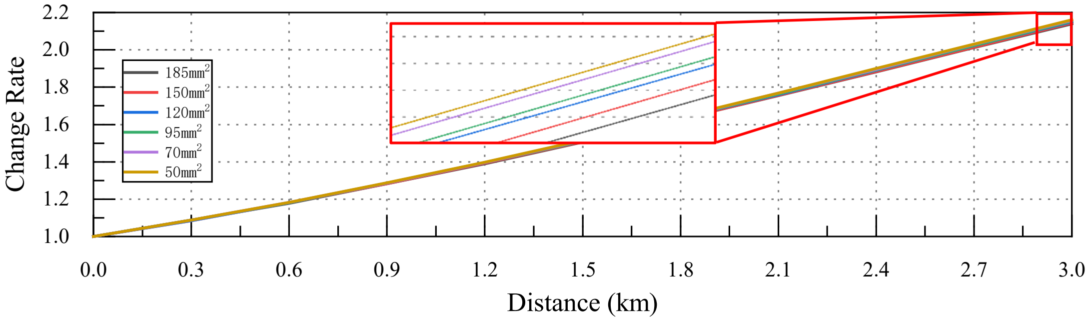
Conductor Section (mm^2)	50	70	95	120	150	185
Reactance (Ω)	0.368	0.358	0.342	0.335	0.319	0.301
Resistance (Ω)	0.63	0.45	0.33	0.27	0.21	0.17
Outer Diameter (mm)	20.1	22	24	25.5	27.3	29



(a) Amplitude Change Rate with Propagation Distance

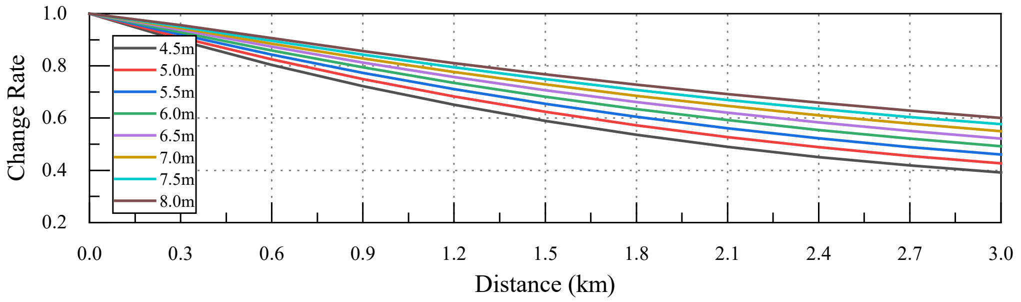


(b) Front Time Change Rate with Propagation Distance

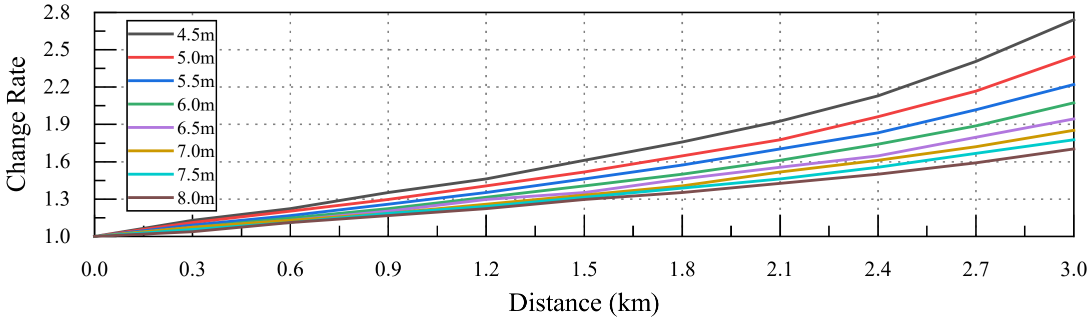


(c) Tail Time Change Rate with Propagation Distance

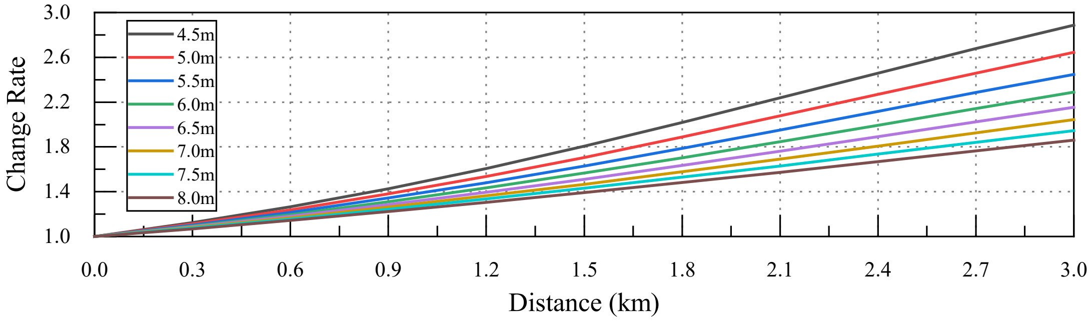
Figure 8: Pulse Current Propagation Characteristics of Different Conductor Sections.



(a) Amplitude Change Rate with Propagation Distance



(b) Front Time Change Rate with Propagation Distance



(c) Tail Time Change Rate with Propagation Distance

Figure 9: Pulse Current Propagation Characteristics of Different Conductor Heights.

3.4. Simulation Results with Different Conductor Height

According to distribution overhead line design code, the height of distribution overhead line shall not be less than 6.5m in residential areas, 5.5m in non-residential areas, and 4.5m in difficult construction areas. Therefore, the heights 4.5m, 5.0m, 5.5m, 6.0m, 6.5m, 7.0m, 7.5m, and 8.0m are used in this paper. By changing the value of conductor height in default parameters, simulation results showed in figure 9 are obtained.

According to figure 9, it can be argued that the amplitudes decrease while front and tail times increases with the propagation distance. The variation degree of waveform patterns is decreased together with the increase of conductor height. Different from the case of different conductor sections, the change of the conductor height has a great influence on the three change rates. The maximum difference between the change rates at a height of 4.5m and a height of 8.0m can reach 30%.

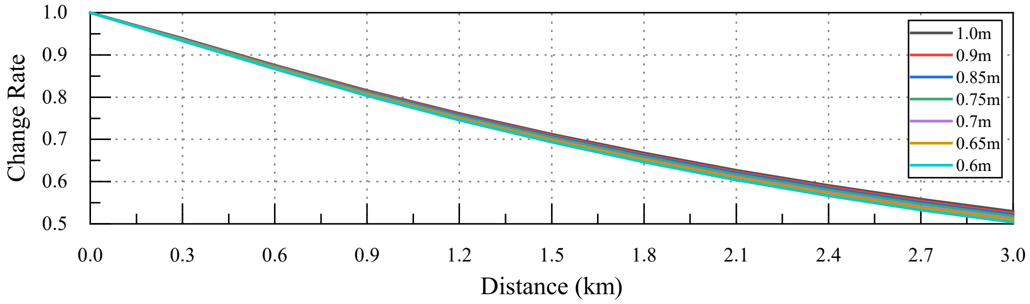
3.5. Simulation Results with Different Phase Distance

According to distribution overhead line design code, the phase distance is related to the tower distance as showed in table 4 below. The distances 0.6m, 0.65m, 0.7m, 0.75m, 0.85m, 0.9m, and 1.0m are used in this paper. By changing the value of phase distance in default parameters, simulation results showed in figure 10 are obtained.

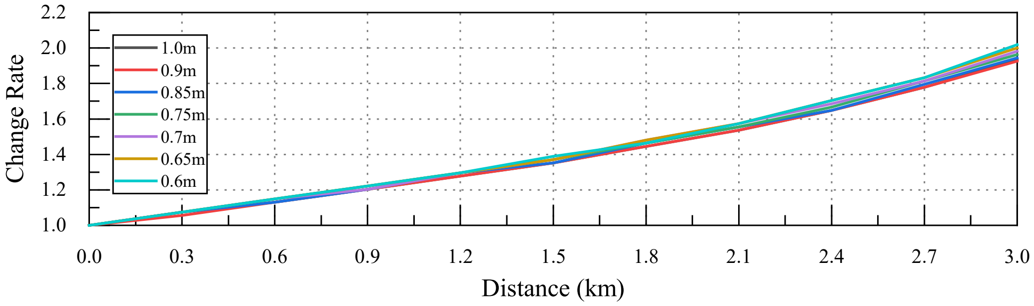
According to figure 10, the amplitudes also decrease while front and tail times still increases with the propagation distance. The variation degree of waveform patterns is decreased together with the increase of phase distance. The change of the phase distance has effects on the three change rates. The maximum difference between the change rates between 0.6m and 1.0m phase distances is about 6%.

Table 4: Phase Distance List.

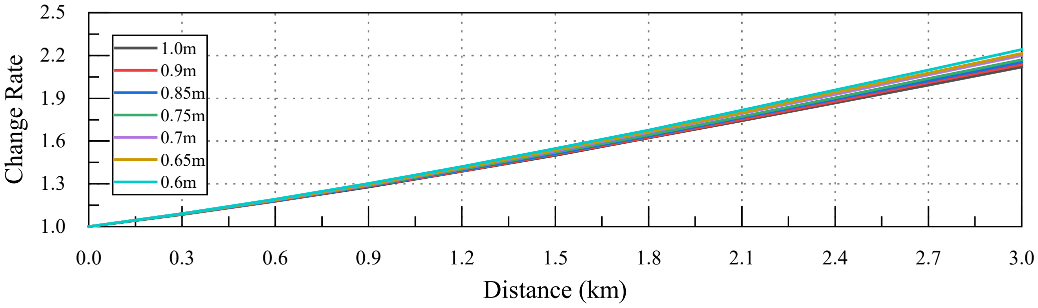
Tower Distance (m)	≤ 40	50	60	70	80	90	100
Phase Distance (m)	≥0.6	≥0.65	≥0.7	≥0.75	≥0.85	≥0.9	≥1.0



(a) Amplitude Change Rate with Propagation Distance



(b) Front Time Change Rate with Propagation Distance



(c) Tail Time Change Rate with Propagation Distance

Figure 10: Pulse Current Propagation Characteristics of Different Phase Distances.

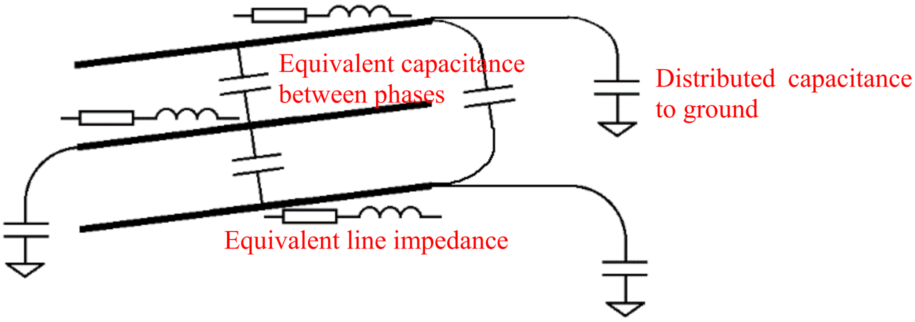


Figure 11: Distribution Parameters of Overhead Line.

3.6. Discussions

3.6.1. Change Rate of Pulse Current Patterns

According to figure 7, the frequency of the pulse current itself has a great influence on its propagation characteristics. It can be argued that the higher the frequency of the signal, the shorter its propagation distance. In the meantime, according to the simulation results in figure 8 to figure 10, the distribution parameters determined by overhead line structure is also able to affect propagation characteristics. The reduction of the conductor height, the reduction of the phase distance, and the reduction of the conductor sectional area can both increase the attenuation of the pulse current transmission along the line. Among them, the conductor height has the highest influence on propagation characteristics. For example, in a propagation distance of 1km, the pulse amplitude in 4.5m high covered conductor will be attenuated by 7% more than 8m height. On the other hand, conductor section has the least influence on propagation characteristics. Comparing the covered conductor with the cross-sectional area of 50mm^2 and 180mm^2, the pulse current amplitude attenuation difference is less than 0.5%/km. Similarly, the change of the phase distance of the conductors has little effect on propagation characteristics. Comparing the covered conductor system with the phase distance of 0.6m and 1.0m, the pulse current amplitude attenuation difference is about 1%/km.

Figure 11 above shows the schematic diagram of overhead line distribution parameters. Overhead lines can be equivalent to a series of multiple L-type or Π-type low-pass filter. As the filter cut-off frequency is inversely proportional to the capacitance and inductance, the attenuation rate of the pulse current will increase together with the signal frequency, capacitance, and inductance. In the overhead lines, the distributed capacitance value will increase with the reduction of the line height and phase distance. This causes the low-pass filter cutoff frequency to decrease, resulting in rapid attenuation of high-frequency components in the pulsed current. As listed in table 3, the reactance and resistance increase with the decrease of conductor section area. Therefore, small conductor section means high conductor impedance and low cut-off frequency, resulting in an increase in the attenuation of the high-frequency components in the pulse current. Since the pulse current of partial discharge is double exponential broadband signal, its high frequency component will decay faster than the low frequency component during propagation. Thus, the time domain waveforms acquired at different measurement points have different shapes.

In summary, under the condition of the single-circuit distribution covered conductor system, when the height of the wire increases by 0.5m, the amplitude attenuation rate will decrease by about 0.1%/100m, the growth rate of the front time will decrease by 0.25%/100m, and the growth rate of the tail time will decrease by about 0.2%/100m. When conductor section area or phase distance changes for 25mm^2 or 0.5m respectively, the variety of three change rates are all less than 0.01%/100m.

3.6.2. Feasibility of Equipment Status Evaluation

In the field of AI evaluation and recognition, the combination of signal patterns can form a unique "fingerprint". Each fingerprint can represent a related scenario. In equipment status evaluation based on partial discharge, using pulse current patterns are the best option [13]. Therefore, it is important to measure the pulse current on covered conductor system. However, limited by the actual overhead line structure and cost, it is unrealistic to install pulse current detection device at each tower of the distribution network. A more reasonable solution is to imitate the existing fault indicator solution [17]. Several measurement devices are fixed on the covered conductor at a certain interval. Each measurement unit can monitor the pulse current within a certain distance on both sides of it. Then, the pulse current can be sampled and recorded for further analysis.

Using Rogowski coil to measure pulse currents has been experimentally successfully used for partial discharge detection in overhead lines. Devices of amplification and filtering can also be added to the output side of the coil to complete the preprocessing of measurement signals [18]. In modern digital measurement system, the triggering of the recording device mainly depends on the amplitude of the input signal. Thus, only if the target signal amplitude is higher than the background noise, it will be recorded and be used to determine whether a partial discharge has occurred.

In order to meet the requirements of equipment state evaluation, the waveform of pulse current will be analyzed. Hence, the Signal to Noise Ratio (SNR) must be large enough to ensure the accuracy of the waveform pattern extraction. According to the propagation characteristics obtained above, it can be seen that the attenuation of the pulse current amplitude must be considered. One measurement point obviously cannot meet the partial discharge detection requirements for the entire distribution line. Ignoring the shunting effect of branch lines in distribution network, the amplitude attenuation rate of the pulse current can reach up to 6.3%/100m. If the maximum attenuation rate of 90% is acceptable, it is necessary to arrange a measuring point every 2.8km.

4. Conclusion

In this paper, the propagation characteristics of the partial discharge pulse current generated at distribution network tower head is obtained and analyzed. The feasibility of equipment status evaluation for this circumstance is also discussed. The main conclusions and achievements are as follows.

For the single-circuit overhead covered conductor system, the change of the partial discharge pulse current waveform during propagation is clarified: according to the line distribution parameters, the amplitude attenuation rate of the pulse current is between 1.5%/100m and 6.3%/100m. the front time growth rate is between 1.5%/100m and 5.7%/100m, and the tail time growth rate is between 1.5%/100m and 3.6%/100m.

The factors that can affect the pulse current propagation characteristics are: the frequency of the pulse current itself, the height of the covered conductor to the ground, the phase distance and cross-sectional area of the conductor. Among them, when the frequency of the pulse current itself and the height of covered conductor can affect the propagation characteristics greatly. In contrast, the phase distance and conductor section have little effect on the propagation characteristics.

According to the propagation characteristic of amplitude, it is clarified that the distance between two adjacent measurement points on the covered conductor system should not exceed 2.8km.

Our future research works will be focused on measuring the partial discharge pulse current in the real distribution covered conductor systems. The measurement results will be used to compare the difference between the actual situation and the simulation. A database with pulse current patterns can be built and equipment status evaluation will be studied.

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