An Incipient Fault Location Method Based on Impedance Calculation

Xintong Liu*
School of electrical and information engineering, Jiangsu university, Zhenjiang 212000, China

*Corresponding author:775407992@qq.com

Abstract. Incipient faults are precursors to permanent faults. The location of incipient faults can effectively prevent permanent faults and reduce the losses caused by faults. In this paper, the Mary fault model is used to simulate the incipient faults by using the arc gap theory to study the incipient fault current and voltage waveform characteristics. An incipient fault location algorithm is proposed on the fault voltage and current waveform characteristics. The line reactance and fault location are obtained by least squares method. Optimizing the algorithm reduces the amount of computation and preprocessing the results to reduce the interference of the error. Finally, a 10kV single-core cable model was built by PSCAD/EMTDC to verify the reliability of the algorithm.

Key words: Incipient Failure, Fault Location, Arc Model, Single Core Cable, Least Squares Method

1. Introduction
With the development of urban distribution network, power cables gradually replace overhead lines with their advantages of small area, no obstruction to city traffic and strong weather resistance. However, as the cable is buried deep underground, compared with the overhead line, it is not easy to conduct manual inspection. Besides, with the growth of cable service time, the cable continues to age and the influence of soil moisture mechanical stress in the external environment, partial discharge and water-tree phenomenon will occur in the cable, resulting in continuous deterioration of insulation effect. Insulation deterioration makes water permeate into the joint will produce arc and evaporation of water, high pressure steam to extinguish the arc, incipient fault self-cleaning. With the increasing frequency of incipient failure, it will eventually develop into permanent failure, causing serious economic losses. Therefore, it is particularly important to monitor and locate the incipient failure of cables.

Cable incipient faults can be divided into semi-periodic incipient faults and multi-periodic incipient faults. The duration of the former is usually 1/4 cycle, while the latter is 1-4 cycle [1]. There have been many studies [2-8] on incipient fault detection. Literature [2] collected data of secondary distribution network and analyzed fault waveform, and extracted fault characteristics through wavelet analysis. Literature [3] collects fault current through kalman filter and determines whether incipient fault occurs through variance of fault current and estimated current of incipient fault. Literature [4] combined wavelet transform with grey correlation analysis method, selected time-domain characteristic quantity by wavelet transform, calculated the grey correlation degree between time-domain characteristic
quantity and reference samples classified as incipient fault of cable, and judged that the incipient fault of cable had the largest correlation degree. Literature [5] analyzes the mutation information in fault signals by using bayesian variation points and combines neural network to detect incipient faults. In literature [6], an arc module was proposed to replace the incipient fault, so as to facilitate simulation analysis.

There are many research achievements on incipient fault detection and recognition at home and abroad, but there are few studies on fault location of incipient fault. In this paper, PSCAD/EMTDC is used for modeling and square wave fault location of incipient fault voltage fitting. On this basis, the algorithm is simplified.

2. Cable Incipient Fault Analysis
The duration of incipient cable faults is generally 1/4 cycle, which usually occurs at the peak voltage and self-extinguishes as the current crosses zero. Due to the short duration, the response of the over-current protection device cannot be caused. This phenomenon is similar to intermittent arc grounding, so it is considered to simulate incipient fault by arc.

Researches on arc models have lasted for decades. Literature [7] proposed Mary and Cassie arcs, among which Mary arc model is suitable for analyzing zero rest period of arc and has excellent low resistance characteristics [8]. Therefore, this paper chooses Mary model to imitate incipient faults.

The electrical conductivity differential equation of the arc is:

\[
\frac{dg}{dt} = \frac{1}{\tau} (G - g)
\]  

(1)

The conductance G for arc stability condition, G for arc conductance, \( \tau \) as the arc time constant. \( \tau \) physical meaning is the energy change in the arc gap makes the arc resistance change 2.73 times as long, its response to the size of the arc voltage is rising faster, formula for \( \tau = \frac{\alpha I}{L} \)  

(2)

In the formula, \( \alpha \) is a constant coefficient, I is peak arc current, L is arc length. The physical meaning of G is arc steady-state conductance, and the formula is:

\[
G = \frac{|i|}{vL}
\]  

(3)

Where, \( i \) is arc current, \( v \) is static voltage drop of arc voltage per unit length, and usually 15V/cm, L is arc length.

The results obtained from equations (2) and (3) are returned to (1). PSCAD/EMTDC is used to model the incipient failure, and the calculated value is transmitted to the variable resistance, so as to present the electrical characteristics of incipient fault in the circuit.

According to equation (1) - (3), arc conductance is controlled by arc length, and the arc length is set to 50cm. The incipient fault voltage and current of 1/4 cycle are shown in figure 1.

![Incipient fault waveform of 1/4 cycle](image_url)
3. Incipient Fault Location Algorithm Based on Impedance

Since incipient cable faults often occur in cable lines of 10kV and below, the influence of distributed capacitance on the line can be ignored. According to the equivalent circuit, Kirchhoff voltage formula can be listed as follows:

$$V = I_f \times R + \frac{dI_f}{dt} \times L + \text{sign}(I_f) \times V_{arc}$$

(4)

Where, V is the voltage monitor set at the first section of the line, which can measure the voltage at the first end of the cable. R and L are the equivalent impedance of the cable, $V_{arc}$ is the arc voltage value, and $I_f$ is the fault current flowing through the line.

The current on the fault phase usually includes the load component, and the current at the neutral point is completely composed of the fault flow. The error can be reduced by collecting the current at the neutral point $I_n$ instead of the fault phase current $I_f$.

Rewrite formula (4) as a matrix:

$$[V] = [I_n \quad \frac{dI_n}{dt} \quad \text{sign}(I_n)] \times \begin{bmatrix} R \\ L \\ V_{arc} \end{bmatrix}$$

(5)

It is obvious that equation (5) equations are overdetermined equations, which cannot be solved by conventional methods, so the least square method needs to be introduced.

As shown in figure 2, when the window is too small, it is easy to be affected by noise interference, while too large a window will cause calculation errors and affect the reliability of the algorithm. Therefore, the selection of the window should be large enough but not exceed the fault duration. In incipient faults, the minimum fault duration is 0.005s (50Hz), so the window should not exceed 50 under the condition that the sampling frequency of the system is 10kHz.

![Fig. 2 Impedance diagram when window length is 20](image)

After selecting an appropriate window, a curve with fluctuations can be obtained, but the estimated value of fault distance is a certain value, so the calculated data should be processed as follows to make the fault distance more accurate:

1. Take the average value: take the average value of the calculated data of the least square method at fault time to get the unique estimate value.
2. Median: median refers to the number in the middle of all data, and the value of median is less affected by extreme data than that of average.
3. Re-substitution method: put the calculated arc voltage, resistance and inductance back into formula (5), and compare the calculated voltage value with the voltage measured by the sensor. Take the group of data with the smallest difference between the two as the best estimation value.

The occurrence of incipient faults is often random, and with the passage of time, the frequency increases and eventually the permanent fault occurs, so it is impossible to calculate the reactance of the cable all the time. Incipient faults have a shorter duration than permanent faults, so they can be screened from permanent faults by fault time. The second is the current threshold value. When there is no incipient failure, the three-phase equilibrium neutral point current is very small, and only when the failure occurs...
will the current change dramatically. By setting the neutral current threshold, computing time can be reduced and system utilization rate can be improved.

4. The Simulation Verification
Incipient faults often occur before permanent faults, so locating incipient faults can avoid permanent faults. A 10kV distribution network line is constructed through PSCAD/EMTDC, as shown in FIG. 3. The cable cross-sectional area is about 260mm squared, the line length is 50km, and the incipient faults are set at 25km from the power supply in phase c.

![Fig. 3 System simulation diagram](image)

After simulation, the neutral current and fault phase voltage are obtained and applied to the incipient fault location algorithm. The resulting fault estimation curve is shown in figure 10. Due to the protrusion of the incipient fault voltage, the incipient multi-period fault curve is not very flat and there are some fluctuations, as shown in FIG. 4. Meanwhile, the exact value of the fault obtained should be a certain value, so the median value of the obtained data can reduce the influence of extreme data. The median value of the obtained data was taken to eliminate the errors, and the data were respectively 25.2477km with errors less than 2%, which had good accuracy.

![Fig. 4 Range diagram](image)

5. Conclusion
In this paper, the Mary arc module is used to simulate the incipient failure of 10kV cable, which is basically consistent with the incipient failure voltage and current waveform measured in other literatures, so as to better simulate the failure. On the basis of this model, an algorithm for incipient fault location is proposed, and the algorithm is simplified to reduce the computational burden, and the accuracy is improved by data preprocessing. At last, the simulation software PSCAD/EMTDC is used to establish the actual circuit model to verify the reliability of the algorithm, which lays a foundation for future research.

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