Fault classification and faulted phase selection for transmission line using morphological edge detection filter

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Abstract: In this paper, a novel algorithm for detecting and classifying faults in transmission lines is proposed. The algorithm is based on mathematical morphology (MM) and initial current traveling waves. A new mathematical edge detection (MED) filter to extract the transient features from the original fault signal is designed. This MED filter can fast and accurately detect the arrival time and polarity of traveling waves in all conditions. The appropriate criteria of fault classification and faulted-phase selection are introduced based on polarity of initial current traveling waves. The simulations based on the electromagnetic transients program (EMTP) and MATLAB have been done to evaluate the validity of the proposed algorithm.

1. Introduction

Fast and accurate detection of faults on the transmission lines is the main objective of any protective relaying scheme. Time required to clear the faults and to isolate the faulted line from the rest of the power system helps in faster maintenance and restoration of power supply. Fault detection and classification to realize the fault type and select the faulty phase are essential for single-pole tripping and auto-reclosing action. Moreover, these functions improve reliability, stability and economy of the power system. Therefore, it is essential to have an efficient algorithm for detecting and classifying transmission line faults.

A variety of fault detection methods for power transmission lines protection have been proposed in recent years [1-9]. Some of these methods are based on power frequency components [1-4] and some others are based on high – frequency components [5-9]. In general, transmission line fault detection includes three aspects: 1) sensing the fault by extracting the transients’ features from the original fault signal; 2) classifying the fault; and 3) locating the fault. Some of the algorithms cover all the three aspects [10-13], while some others focus on one or two of the aspects [14, 15]. Extracting the features from the fault signal is the most important issue in all fault detection algorithms. There are many methods for feature extraction such as fast Fourier transforms (FT) [16], Kalman filter [17], wavelet transforms (WTs) [18, 19], and S-transform (ST) [20].

WT is an efficient tool of analysing the transient signal in both frequency and time-domain. This transform is widely used in transmission lines protection [21-24]. In some approaches, WT has been combined with other techniques such as artificial neural networks [25], fuzzy logic [26, 27] and singular value decomposition (SVD) [23, 28] to improve the performance of the proposed protection algorithm. In [29], a technique for transmission line fault recognition and classification using multiwavelet packet transformation, entropy, and ANN is proposed. Ananthan et al. [30] have used wavelet multi-resolution analysis for fault detection and classification of a 200 km transmission line. Mahamedi and Zhu in [31] have used symmetrical components of reactive power for fault classification and fault phase selection in transmission lines.

Travelling-wave-based fault detection methods [32-35] are widely used in transmission lines because of their advantages such as high accuracy and reliability. Transient signals of travelling waves contain extensive information about the fault type, fault location, and fault direction, which have been used to design many fast protection algorithms. Extracting the fault information from the traveling wave is an important issue, which can have a significant impact on the accuracy of the algorithm. In these methods, wavelet transform as a strong mathematical tool is used for processing high-frequency transient signals. However, it may be influenced by faulty conditions such as high impedance fault and low inception angle, resulting in declined amplitude of travelling waves. In [36], a high impedance fault detection method based on MM is presented for the distribution system. The combination of mathematical morphology, singular value decomposition, and entropy theory is also proposed for phase selection [37]. However, the MM filter used in these methods could only detect the amplitude of traveling waves and could not detect the polarity.

In this paper, a new MED filter is applied for design of a fault detection and classification method. First, appropriate criteria for different type of faults based on the polarity of initial current traveling waves on one side of the transmission line are introduced. Then, the MED filter is applied for processing high-frequency transient signals and detecting polarity of initial current traveling waves. The major contribution of the proposed method is using the MED filter which its outputs are only “+1”, “-1” or “0” for any type of faults. The MED filter uses only addition, subtraction, and comparison operations also use a short data window for processing fault signals. Therefore, the fault detection and classification by the proposed method can be done easily, quickly and accurately.

The paper is organised as follows. The mathematic method of design of the proposed MED filter is described in Section 2. In Section 3, characteristics of various faults are described by the Karenbauer transform-based phase-modal transformation. Then, the algorithm for fault classification and faulted-phase selection is proposed. In Section 4,
simulation results for the typical 500 kV transmission system and the IEEE 14-bus systems with various fault conditions are provided. At last, the conclusion is drawn in Section 5.

2. Mathematical method of filter design

2.1. Mathematical morphology

Mathematical morphology (MM) is a non-linear analysis technique with high accuracy and low computation burden, which can be used for extracting the information of high-frequency signals that result from different power system disturbances. The MM focuses on the form, shape and size of signals in the time domain and needs a shorter data window [38]. The structural element (SE) is the basic of the morphological filter, which is used for extracting the features of original signals. The selection of SE is important and depends on the particular application. An SE could have different shapes, some of which are flat, square, curve, triangular, and semi-circular [39]. In power systems in which signals are one-dimensional, the most suitable SE is flat. In this paper, the flat SE \( g(m) = \{0,0,0\} \) was considered.

Dilation and erosion are two basic operations in the MM. Based on these two operations, other compound operators such as opening and closing are defined. Assuming that \( f(n) \) is the input signal defined as discrete function at amplitude \( D_f = \{0,1,2, ..., N-1\} \) and \( g(m) \) is an SE defined at amplitude \( D_g = \{0,1,2, ..., M-1\} \), then dilation of signal \( f \) by \( g \), denoted by \( (f \oplus g) \), and erosion of signal \( f \) by \( g \), denoted by \((f \ominus g)\), are defined as [38]:

\[
\begin{align*}
    f_d(n) &= (f \oplus g)(n) = \max\{f(n-m)+g(m)\} \\
    f_e(n) &= (f \ominus g)(n) = \min\{f(n+m)-g(m)\}
\end{align*}
\]

where \( n \in D_f \) and \( m \in D_g \). Using the two basic operations described in (1) and (2), two other operators called opening and closing are obtained. The opening of signal \( f \) by \( g \), denoted by \( f \ast g \), and the closing of signal \( f \) by \( g \), denoted by \( f \ast g \), are defined as:

\[
\begin{align*}
    f_o(n) &= (f \ast g)(n) = ((f \oplus g) \ominus g)(n) \\
    f_c(n) &= (f \ast g)(n) = ((f \ominus g) \oplus g)(n)
\end{align*}
\]

By combining the four operations introduced in (1) - (4), several MFs have been proposed in [39]. Although these MFs properly eliminate the majority of the noise and detect changes in the signal domain, they are not able to detect polarity. Thus, to solve this problem, a new morphological edge detection (MED) filter is proposed in this paper. In fact, the function of the new filter is similar to the filter proposed in the previous work [40]. However, the new filter can detect the signal polarity with more precision and clarity.

2.2. Proposed MED filter

Edge detection is a fundamental tool to identify and locate sharp discontinuities in images and signals. There are many methods to perform edge detection. The majority of these methods may be grouped into two categories: gradient and laplacian. The laplacian methods use the second derivative order and detect edges by looking for zero crossings in the second derivative. The gradient methods use the first derivative order and detect edges by looking for the maximum in the first derivative. Several edge detection operators like Sobel, Robert and Prewitt are based on gradient. In this paper, the Sobel operator is used as an edge detection operator. In general, the gradient of an image as a function of two variables, \( f(x, y) \), is defined as [41]

\[
G[f(x, y)] = \begin{bmatrix} G_x \\ G_y \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \end{bmatrix}
\]

However, the gradient of a signal \( f(x) \) (which, in one dimension, is just the first derivative with respect to \( x \) can be defined as

\[
G[f(x)] = G_x = \frac{\partial f}{\partial x}
\]

It is clear that, in edges of the signal, the gradient has maximum value. Therefore, finding the location of an edge is to locate the maximum in the first derivative. Consider open-close and close-open median (OCCOM) filter as [41]:

\[
OCOM(n) = (f(n) \ast (f \ast g))(n) \\
+ (f(n) \ast (f \ast g))(n)/2
\]

OCOM filter is the most appropriate filter to remove the noise from the original signal. So, it is used to design the proposed filter in this paper. Based on (1) and (2), two filters can be obtained from OCCOM filter as follows:

\[
MF_1(n) = OCCOM_d(n) = (OCOM \ast g)(n)
\]

\[
MF_2(n) = OCCOM_c(n) = (OCOM \ast g)(n)
\]

where \( MF_1(n) \) and \( MF_2(n) \) are defined as dilation and erosion of the OCCOM by \( g \), respectively. Interesting point in processing a signal by \( MF_1(n) \) and \( MF_2(n) \) is that the \( MF_1(n) \) leads the \( MF_2(n) \) when there is an ascending edge, and lags the \( MF_2(n) \) when there is a descending edge. Also, when there is no sudden change in the original signal, \( MF_1(n) \) and \( MF_2(n) \) signals are in phase. Therefore, using this important characteristic and edge detection technique, the proposed MED filter is defined as

\[
MED(n) = Edg(MF_1(n)) - Edg(MF_2(n))
\]

where \( Edg(MF_1(n)) \) and \( Edg(MF_2(n)) \) are the edge of \( MF_1(n) \) and \( MF_2(n) \), respectively. Fig. 1 represents the outputs of \( MF_1 \), \( MF_2 \) and \( MED \) on a typical fault current signal \( j(t) \). It can be observed that the proposed MED filter can accurately and clearly detect the signal polarity. Also, the MED output is always “+1”, “+1” or “0”. Thus, using the proposed MED filter, the polarity of the initial current traveling wave can be detected accurately.