A Study on Power Quality Transient Disturbance Location Method

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Abstract. Due to periodic variation of power signal and various disturbances present during sampling process, resulting background gradient affects the accuracy of disturbance detection. In order to solve this problem, this paper proposes a power quality transient disturbance location method based on morphological edge detection, and introduces a soft threshold quantitative evaluation method to improve its accuracy. Firstly, an evaluation method of filtering effect is proposed, and original signal is filtered by adaptively choosing size of structuring elements. Then, Top-Hat transform of morphological gradient is performed by flat structuring elements to suppress background gradient, and the location result is initially obtained. Finally, combined with soft threshold processing method, the location of power quality transient disturbance is realized. Simulation analysis of a series of power quality transient disturbances shows that this algorithm has accurate location results, strong capacity of resisting disturbance and good versatility.

Key words. power quality; disturbance location; background gradient; morphological edge detection;

1. Introduction

Recently, power quality problems are increasingly concerned by suppliers and customers of electricity. Various transient disturbances, such as voltage sag, swell and momentary interruption, are becoming more and more prominent. Correct early warning, protection and other functions of intelligent electrical apparatus are based on accurate location of disturbance signals. Therefore, accurate locating transient disturbance of power quality is the basis for improving power quality and protecting safety of electrical equipment. At present, main power quality processing methods include Fourier method, wavelet transform, neural network and mathematical morphology etc. Fixed-time window defect of Fourier method [1] limits its ability to analyze transient disturbance; wavelet transform [2-5] is sensitive to noise, and its variable window width as well as high sampling frequency increase computational load, leading to difficulties of achieving real time; neural network method [6-7], which is used for disturbance detection, having shortcomings of massive samples, complicated training, slow convergence, easy convergence to local minimum, etc., is difficult to satisfy practical applications. Detection method based on mathematical morphology theory has achieved many fruitful results in power quality disturbance location [8-13]. In this method, signals are processed only by adding, subtracting and taking extreme values, so calculation speed is fast; but when filtering signals, size of structuring elements is often determined according to experience, which results in reducing of applicability. Moreover, locating disturbance by searching local maximum is lack of quantitative evaluation standard and reliable basis, which has certain randomness and reduces credibility of
location result.

Based on researches of traditional morphological edge detection method in power quality transient disturbance location, this paper adopts morphological filtering algorithm of adaptively choosing size of structuring elements, and proposes choice basis and method; Top-Hat transform is applied to morphological gradient of flat structuring elements to effectively suppress influence of background gradient; Soft threshold processing method is introduced to improve accuracy, and final location result is obtained. According to this flow, typical transient disturbance signals are taken as examples to perform simulation verification.

2. Rationale of morphological edge detection and background gradient

2.1. Fundamental principle of morphological edge detection

Mathematical morphology, mainly gray value morphology in power signal processing, has definition of morphological opening and closing as follows:

\[ f \ominus g = f \Theta g \ominus g \]  \hspace{1cm} (1)

\[ f \bullet g = f \Theta g \ominus g \]  \hspace{1cm} (2)

Where \( f \) is power signal; \( g \) is structuring element; \( \ominus \) is dilation operation; \( \Theta \) is erosion operation; \( \ominus \) and \( \bullet \) is morphological opening and closing operation respectively.

In image edge detection method [14-16], the edge of image is a reflection of local discontinuity. The essence of this method is to detect the location where image texture feature changes. Similarly, starting and ending locations of transient disturbance can be regarded as the edge, so that the location problem can be transformed into edge detection problem.

Common edge detection operators are mainly as the following:

1) Dilation edge detection operator is:

\[ \alpha_1 = (f \Theta g) - f \]  \hspace{1cm} (3)

2) Erosion edge detection operator is:

\[ \alpha_2 = f - (f \Theta g) \]  \hspace{1cm} (4)

3) Morphological gradient operator of dilatant erosion type is:

\[ f_{grad} = (f \Theta g) - (f \Theta g) \]  \hspace{1cm} (5)

4) Top-Hat transform for detecting peaks is:

\[ f_{HAT} = f - (f \ominus g) \]  \hspace{1cm} (6)

When there is no mutation in detection signal, gray value of each point falling in structuring element window is similar, the original signal is not much different from its dilation and erosion operation results, so output of edge detection operator is small; However, in the location of mutation, there is a big difference between original signal and its operation results, resulting in a large output of edge detection operator.

2.2. Analysis of background gradient

In image processing, change of gray value is usually summarized into two cases of ramp change and step change. The power signal with periodic variation changes slowly under normal conditions, similar to the ramp change, and the mutation is like the step change.

When image edge detection is used to locate power quality disturbance, even in absence of disturbance, edge detection operator has a certain output value, which is called background gradient. This is because that, according to \( f \Theta g \leq f \leq f \oplus g \), due to periodic variation of signal \( f \) and non-stationary caused by noise, results of dilation and erosion are different, so that morphological gradient of the difference between two operations is not zero. Take Figure 1 as an example, Figure 1(a) is noise power frequency sinusoidal signal \( f_0 \), Figure 1(b) is background gradient output \( f_{grad} \) processed by morphological gradient operator. The amplitude of sine-like output in Figure 1(b) is mainly caused by periodic variation of power signal, and the glitch is generated by noise. In practical applications, background gradient is the main influence factor in power quality transient disturbance location. For
this reason, edge detection of transient disturbance should avoid influence of ramp change, and correctly distinguish step change as the edge of disturbance signal.

Output of edge detection operator of signal is related to the slope of ramp and the length of structuring elements. The larger of absolute value of slope, the longer of structuring elements, and the larger of output. For step change, output is always the height of step change regardless of the length of structuring elements. When the slope of ramp is large and the width is narrow, the length of structuring elements is greater than the width of ramp, so that output is the height of ramp, in this case ramp change is converted into step change. In general, background gradient can be suppressed by choosing shorter structuring elements to increase sampling rate, etc., but too short structuring elements may not be able to distinguish step change, resulting in edge detection failure.

Assuming that the length of structuring elements of morphological gradient is \( M \), the length of actual corresponding time window is \((M-1)\) sampling periods, and the width of detected signal edge is \(2(M-1)\) sampling periods. In order to ensure that Top-Hat transform will not flatten the morphological gradient produced by step change, length of time window corresponding to structuring elements should be no less than edge width. Therefore, length of structuring elements of Top-Hat transform should be greater than or equal to \(2(M-1) + 1\), ie \((2M-1)\).

### 3. Algorithm for locating transient disturbance of power quality

The power quality transient disturbance location algorithm flow is:

1) Construct the morphological filter. Linear structuring element is chosen as the filtering element, using the morphological filter proposed by Maragos, ie

\[
h = \frac{(f_{oc}(g)) + (f_{co}(g))}{2}
\]  

(7)

Where oc and co is opening-closing and closing-opening operation respectively.

2) Adaptively choose the length \( L_{th} \) of filtering structuring elements. In order to assess the effect of morphological filtering, the signal-to-noise ratio (SNR) \( R_{snr} \) is introduced, defined as

\[
R_{snr} = 10\log_{10}\left(\frac{\sum_{n=0}^{N-1} f_{0}^{2}(n)}{\sum_{n=0}^{N-1} [f_{0}(n) - h(n)]^2}\right)
\]  

(8)

Where \( f_{0}(n) \) is noise-free signal; \( h(n) \) is morphological filtered signal; \( N \) is total sampling points. Then, the length of corresponding structuring elements when the SNR is maximum can be taken as the length of filtering structuring elements.

3) Construct the edge detection operator. The Top-Hat transform result \( f_{HAT} \) of morphological gradient of flat structuring elements is defined as

\[
f_{HAT} = h_{grad} - (h_{grad} \circ g)
\]  

(9)

Where \( h_{grad} \) is morphological gradient of filtered signal \( h(n) \).

By opening operation of morphological gradient, peak formed by disturbance in morphological gradient can be extracted and separated from background gradient generated by ramp change.
Choose the edge detection output threshold. Referring to soft threshold processing method in [17], the calculation formula of noise intensity is

$$\sigma = \left( \sum_{n=0}^{N-1} |f_{\text{HAT}}(n)| / N \right) / 0.6745$$  \hspace{1cm} (10)

Choose output threshold $\sigma_{th}$ of edge detection operator as

$$\sigma_{th} = \sigma \sqrt{2 \ln N}$$  \hspace{1cm} (11)

Then location result $f_{\text{edge}}$ of edge detection is

$$f_{\text{edge}} = \begin{cases} 0, & f_{\text{HAT}} \leq \sigma_{th} \\ f_{\text{HAT}}, & f_{\text{HAT}} > \sigma_{th} \end{cases}$$  \hspace{1cm} (12)

When the output of edge detection operator is greater than chosen threshold, it can be considered as the location of disturbance.

4. Case analysis

Three common power quality transient disturbances, voltage sag, swell and momentary interruption are taken as examples. They are simulated in absence of noise, and compared with wavelet transform results to verify the effectiveness of edge detection method proposed in this paper. Figure 2–4 show detection results of voltage sag, swell and momentary interruption. In these figures, $f$ is disturbance signal; $f_{\text{grad}}$ is morphological gradient; $f_{\text{edge}}$ is soft threshold location result after Top-Hat transform; $d_1$ is high-frequency subband after one layer wavelet decomposition of db3 wavelet. The flat structuring element is chosen for edge detection simulation. The length of morphological gradient structuring elements is 3, the length of Top-Hat transform structuring elements is 5, and the sampling frequency is $f_s = 6.4$ kHz.

![Figure 2](image-url)  \hspace{1cm} ![Figure 3](image-url)

**Figure 2.** Voltage swell detection result.  \hspace{1cm} **Figure 3.** Voltage sag detection result.
From simulation results, due to background gradient, morphological gradient $f_{\text{grad}}$ have extreme values in non-disturbance location too. So it is difficult to determine location of disturbance by searching local maximum without quantitative method. Edge detection algorithm proposed uses the Top-Hat transform to suppress background gradient and the soft threshold quantitative evaluation method to accurately locate disturbances. Table 1 shows location results of various transient disturbances. It can be seen that, maximum average error of edge detection algorithm does not exceed half of the sampling period. In Table 1, $T_s=1/f_s$ is the sampling period.

| Item                      | Voltage swell | Voltage sag | Voltage momentary interruption |
|---------------------------|---------------|-------------|--------------------------------|
| Actual location/ms        | 43.750        | 96.875      | 43.750                         | 96.875                        |
| Location result/ms        | 43.828        | 96.953      | 43.750                         | 97.031                        |
| Location result error     | $0.5T_s$      | $0T_s$      | $T_s$                          | $1T_s$                        |
| Wavelet transform result  | 43.906        | 97.031      | 43.906                         | 97.031                        |
| Wavelet transform error   | $1T_s$        | $1T_s$      | $1T_s$                         | $1T_s$                        |

In the case of noise interference, morphological filtering of disturbance signal is firstly performed. In order to obtain better filtering effect, this paper adaptively choose the length of structuring elements. To verify the effectiveness of this method, voltage sag is taken as an example, adding a certain white noise, and making the SNR $R_{\text{snr}}=36$ dB. Figure 5 and 6 show the location results of noisy and filtered sag signals respectively. Simulation results show that the method combining Top-Hat transform and soft threshold can achieve good location results under noise interference, without false detection; the ability of single Top-Hat transform to suppress background gradient is limited, there is no guarantee that no false detection will occur in strong noise; output of wavelet transform is often overwhelmed by noise.

In order to study the influence of length of morphological gradient structuring elements and Top-Hat transform structuring elements on disturbance location results, the length of structuring elements is changed. The example is still the noisy voltage sag signal $f_1$ in case of noise interference, and the location result is shown in Figure 7. The length of morphological gradient structuring elements in Figure 7(a), 7(b), 7(c) and 7(d) is 3, 5, 7 and 9 respectively, and the length of Top-Hat transform
structuring elements is 5, 7, 9 and 11 respectively.

Figure 5. Noisy voltage sag signal detection result.

Figure 6. Filtered voltage sag signal detection result.

Figure 7. Influence of size of structural elements on location results.

From above simulation results, two conclusions can be drawn: 1) as the length of structuring elements increases, false detection results of location increase. This is because that the increase of length makes the ramp change become the step change, which causes false detection; 2) when the length of structuring elements increases, width of location results also increases, although center value can be taken as the result, the accuracy is still reduced. Therefore, only by choosing appropriate length of structural elements can achieve accurate location results.

To further investigate the performance of edge detection method, Blocks signal in Matlab was used for testing. Figure 8 shows the test results of Blocks signal, $f_B$ is noise-containing Blocks signal, $f_{HAT}$ is
Top-Hat transform, \( f_{\text{edge}} \) is location result of this paper, and \( d_1 \) is wavelet transform result. It is obviously that edge detection algorithm designed in this paper can meet requirements of accurately locating various disturbance signals.

\[
\begin{array}{c}
\text{(a) Blocks signal } f_i \\
\text{(b) Top-Hat transform } f_{\text{HAT}} \\
\text{(c) Location result } f_{\text{edge}} \\
\text{(d) Wavelet decomposition result } d_1
\end{array}
\]

**Figure 8.** Blocks signal detection result.

5. Conclusions

1) The effect of morphological filtering has a great influence on locating power quality disturbance. Using the SNR as the evaluation standard to adaptively choose size of structuring elements for filtering, can meet requirements of removing noise while preserving local characteristics of signals.

2) The size of flat structuring elements as edge detection operators should be chosen according to characteristics of detected signals, in order to avoid false or missed detection due to structuring elements that are too large or too small.

3) This paper analyzes the mechanism of background gradient generation, and the location method which combines ability of Top-Hat transform to suppress background gradient and soft threshold quantification, and improves the accuracy of locating transient disturbance of power quality in various situations.

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